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RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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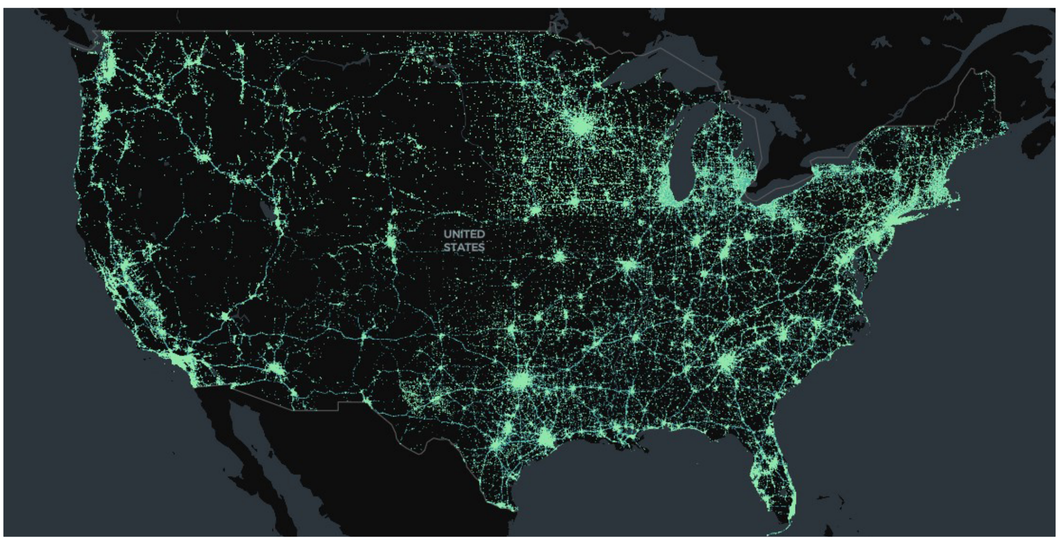
Connected Vehicle-Centric Dashboards for TMC of the Future



Rahul Suryakant Sakhare, Jairaj Desai,
Wyatt Woker, Howell Li, Jijo K. Mathew, Justin Mahlberg,
Enrique D. Saldivar-Carranza, Deborah Horton, Darcy M. Bullock

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AUTHORS

Rahul Suryakant Sakhare
Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

Jairaj Desai, PhD
JTRP Transportation Research Engineer
Lyles School of Civil Engineering
Purdue University

Wyatt Woker
Undergraduate Researcher
Lyles School of Civil Engineering
Purdue University

Howell Li
JTRP Principal Research Analyst
Lyles School of Civil Engineering
Purdue University

Jijo K. Mathew, PhD
JTRP Transportation Research Engineer
Lyles School of Civil Engineering
Purdue University
(765) 494-4521
kjijo@purdue.edu
Corresponding Author

Justin Mahlberg
Enrique D. Saldivar-Carranza
Graduate Research Assistants
Lyles School of Civil Engineering
Purdue University

Deborah Horton
JTRP Managing Director
Lyles School of Civil Engineering
Purdue University

Darcy M. Bullock, PhD, PE
Lyles Family Professor of Civil Engineering
JTRP Director
Lyles School of Civil Engineering
Purdue University

JOINT TRANSPORTATION RESEARCH PROGRAM

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NOTICE

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16. Abstract

The adoption of dashboards and tools into Traffic Management Centers (TMC) has been growing with advancements in connected vehicle (CV) data. These tools are now being utilized—not only for analyzing work zones, severe crashes, winter operations, and traffic signals—but also to provide measures for characterizing overall system mobility, resiliency, and after-action assessments. Previous studies have extended the concepts to include the enhanced trajectory-based CV data into dashboards that aid agencies in assessing and managing roadways. This study presents the extension of these tools that further improve the value and insights provided. It also highlights the evolution of CV data in Indiana. CV data in Indiana has grown to over 364 billion statewide records. Average overall penetration rate of CV data on interstates has increased to 6.32% in May 2022 with trucks accounting for 1.7%. Sections of this study also present the impact of rain intensity on interstate traffic and incorporation of such weather data into heatmap and other tools. Updates to existing dashboards and a summary of newly developed dashboards are synopsized in this report. Finally, this report presents a case study that highlights the use of these tools to assess and analyze the impact of tornadoes on interstate traffic in Indiana. As interest in these tools has grown, this project facilitated continued improvements and added features to meet the needs of INDOT and their partners.

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EXECUTIVE SUMMARY

Motivation

The adoption of dashboards and tools into Traffic Management Centers (TMC) has been growing thanks to advancements in connected vehicle (CV) data. These tools are now being utilized—not only for analyzing work zones, severe crashes, winter operations, and traffic signals—but also for providing measures for characterizing overall system mobility, resiliency, and after-action assessments. Traditional tools are enriched by incorporating newer, higher-fidelity, and complementary datasets. As interest in these tools has grown, this project facilitated the improvements and added features to meet the needs of INDOT and their partners.

Study

Previous studies have extended to concepts that include the enhanced trajectory-based CV data into dashboards that aid agencies in assessing and managing roadways. This study presents the extension of these tools to further improve the value and insights they provide. It also highlights the evolution of CV data in Indiana. This study also assesses the growth in penetration rates after the addition of commercial truck data alongside the passenger car data. Sections of this study also present the impact of rain intensity on interstate traffic and incorporation of such weather data into heatmap and other tools. Updates to existing dashboards and a summary of newly developed dashboards are synopsized in this report. Finally, this report presents a case study that highlights the use of these tools to assess and analyze the impact of tornadoes on interstate traffic in Indiana.

Results and Impact

A summary of the results and key findings from this report are presented below.

- CV data in Indiana has grown to over 364 billion records (Figure 2.1).
- The average overall penetration rate of CV data on interstates has increased to 6.32% in May 2022 with trucks accounting for 1.7% (Figure 2.7).
- Very heavy rain events (precipitation rate greater than 8 mm/hour) have been found to decrease average speeds by 8.4% compared to no rain conditions (Figure 3.4).
- Implementation of the trajectory heatmap tool and improvements to the heatmap and delta speed v2 dashboards (Figure 4.1).
- An impact assessment of tornadoes on interstate traffic (Figure 5.1).

The work zone and hard braking reports disseminated weekly continue to simplify the identification of critical issues and monitor impact from the implementation of any corrective measures in such areas. Furthermore, additional agencies, such as the Indiana Toll Road have now adopted these tools and there is a new FHWA Pooled Fund project on Work Zone Analytics (solicitation 1592) being initiated to facilitate implementation of these reporting metrics in other states.

Recommendations

The main recommendations from this study include, but are not limited to, the following.

- Continue the dissemination of upgrades to the existing tools and engagement with peer stakeholders.
- Continue to support tools (Figure 4.1).
- Continue to incorporate emerging datasets into real-time dashboards.

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LIST OF ACRONYMS

AVL	Automatic Vehicle Location
CV	Connected Vehicle Data
DOT	Department of Transportation
EST	Eastern Standard Time
GPS	Global Positioning System
HRRR	High-Resolution Rapid Refresh
IQR	Interquartile Range
INDOT	Indiana Department of Transportation
ITS	Intelligent Transportation Systems
MM	Mile Marker
NB	Northbound
NOAA	National Oceanic and Atmospheric Administration
SB	Southbound
TMC	Traffic Management Center
USGS	United States Geological Survey
WB	Westbound

1. INTRODUCTION

The Indiana Department of Transportation (INDOT) has expanded the use of connected vehicle (CV) data to develop performance measures and visualization tools using vehicle speeds, hard braking events, and integration of ITS assets such as cameras over the past decade (Day et al., 2016; Desai, Mahlberg, et al., 2021; Li et al., 2018; Mathew et al., 2021; McNamara et al., 2017; Sakhare, Desai, Mathew, McGregor et al., 2021; Sakhare, Desai, et al., 2022; Sakhare, Li, et al., 2022). The penetration levels of CV in Indiana now generate over 14 billion records per month. Specialized tools have been developed on-premises and cloud servers to facilitate real time ingestion, processing, and visualization of this data. This project has continued the development and implementation of those dashboards across multiple areas of the agency.

The coverage of CV data has been growing over the years (Mathew et al., 2021). A 1-minute snapshot of CV data across the nation is shown in Figure 1.1 between 12:00 PM to 12:01 PM eastern time on December 12th, 2022. Major cities and roadways are highlighted by the snapshot. The granular information provided by trajectory-based data has vastly improved the analytics and insights derived from these dashboards. This report will present the evolution of the CV data, the penetration rate, and updates on dashboard developments.

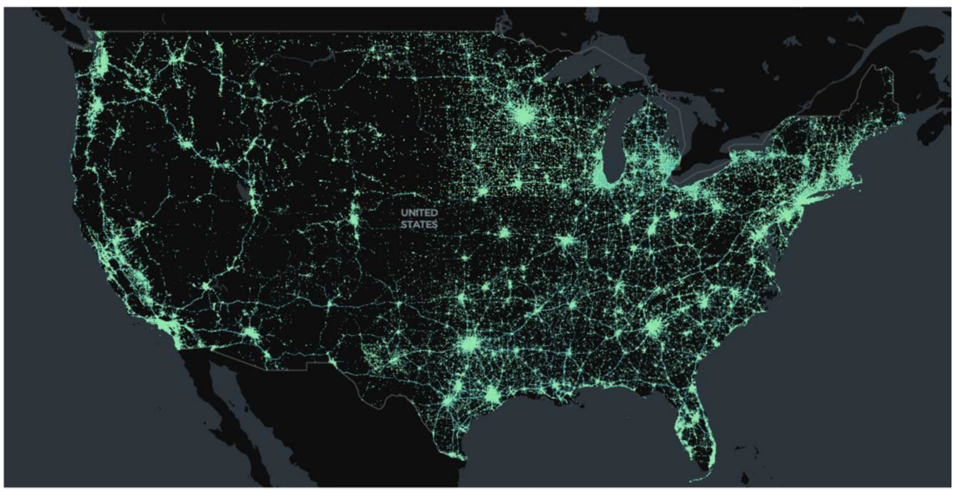


Figure 1.1 National coverage of connected vehicle data, showing 21 million records within a 1-minute duration at 12:00 PM EST on December 12th, 2022.

2. CONNECTED VEHICLE DATA EVOLUTION

Previous reports have highlighted the extent of CV data and several use cases (Mathew et al., 2022; Sakhare, Desai, Mathew, Kim, et al., 2021, Sakhare et al., 2023). Prior to January 2022, CV data was acquired in batches as per use case and exploration basis. Since January of 2022, the CV data has been ingested continuously in real time. Monthly CV data records and growth of total records in Indiana over past few years maintained by Purdue on Google's cloud platform is highlighted in Figure 2.1. The statewide dataset contains more than 364 billion records as of February 17th, 2023.

2.1 Inclusion of Truck Trajectory Data

CV data providers have made strides to provide trajectory data for trucks as well. In general, the CV data consists of anonymized individual trajectory waypoints that are collected every one to three seconds for connected passenger cars and three to sixty seconds for connected trucks along with an anonymized trajectory identifier, geolocation, timestamp, and heading information.

Spatiotemporal traffic speed heatmaps visually analyze the traffic conditions and assess queues as shown by several previous studies (Desai, Sakhare, et al., 2021; Mathew et al., 2022; Sakhare, Desai, et al., 2022). CV trajectory data color coded by speed bins can be used to generate such heatmaps. One such example of a traffic speed heatmap along I-65 northbound from MM 170 to 185 on Wednesday, May 11th and Thursday, May 12th, 2022, is shown in Figure 2.2. The horizontal axis represents the time of the day, and the vertical axis shows the location mile marker on the interstate. Figure 2.2(a) shows 0.53 million records from 3,389 distinct trips of connected passenger cars. Callout i and ii point to the overnight hours with very low to zero availability of connected passenger cars making it difficult to provide any information on traffic conditions during these hours. Figure 2.2(b) shows 50,180 records from 1,866 distinct trips of connected trucks. The additional data provides critical missing traffic condition information during the overnight hours. Combined connected passenger car and connected truck trajectories are shown in Figure 2.2(c). The combined heatmap depicts traffic condition information across all hours of the day especially during the night hours (callout iii and callout iv) that was missing from passenger cars (callout i and callout ii on Figure 2.2(a)). ITS camera images from MM 178.3 along I-65 are shown in Figure 2.3. Callout i and iii from Figure 2.2 corresponds to the image in Figure 2.3(a), and callout ii and iv from Figure 2.2 corresponds to the image in Figure 2.3(b). It can be clearly seen from the camera images that truck traffic is moving through this section of the work zone during the overnight hours. The inclusion of truck data provides a holistic view of the traffic condition and better represents the mix of vehicle classes in the traffic steam.

2.2 CV Data Penetration Rate Updates in Indiana

Traffic counts were obtained from Indiana DOT's traffic count database (INDOT, 2022) and were used to evaluate the penetration of CV (Hunter et al., 2021; Sakhare, Hunter, et al., 2022). Many different technologies are utilized at continuous count stations, such as inductive loops, piezoelectric sensors, and magnetic sensors (FHWA, 2023). Indiana DOT's Statewide Traffic Monitoring System consists of permanent continuous count stations that can collect volume, speed, and vehicle classification data 24 hours per day throughout the year (INDOT, n.d.).

For the purposes of this study, data from 40 such count stations (Figure 2.4) were obtained for the period

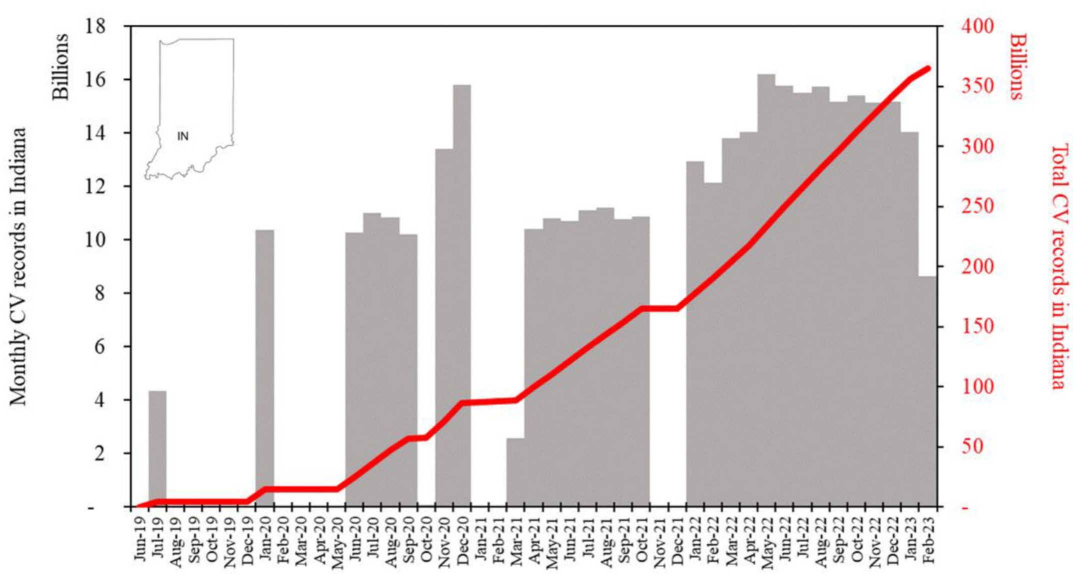
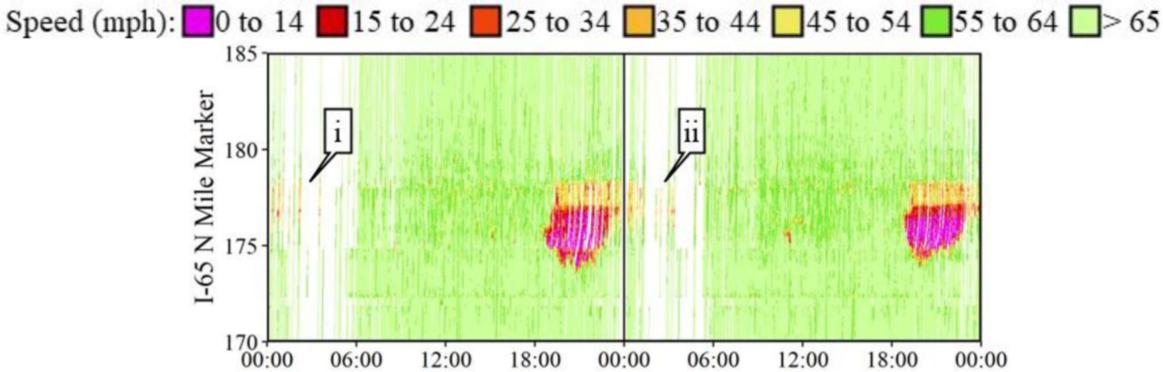
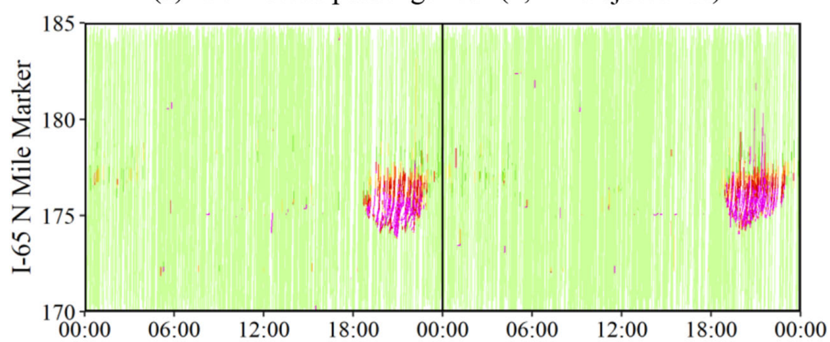


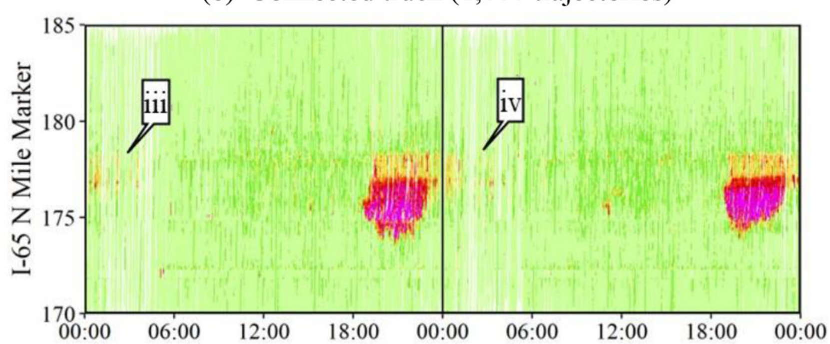
Figure 2.1 CV data records in Indiana (364.6 billion as of February 17th, 2023).



(a) Connected passenger car (3,389 trajectories)



(b) Connected truck (1,866 trajectories)



(c) Combined CV data (5,255 trajectories)

Figure 2.2 Comparison of connected truck and passenger car trajectories.

(a) 2:28 AM on Wednesday, May 11th

(b) 2:34 AM on Thursday, May 12th

Figure 2.3 ITS camera images at MM 178.3 along I-65 at night.

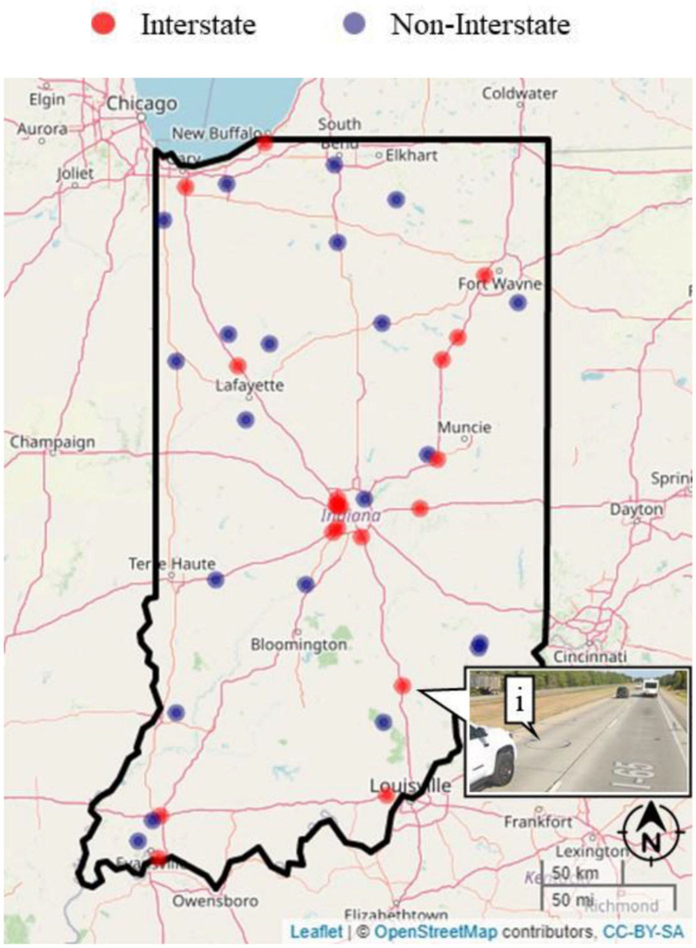


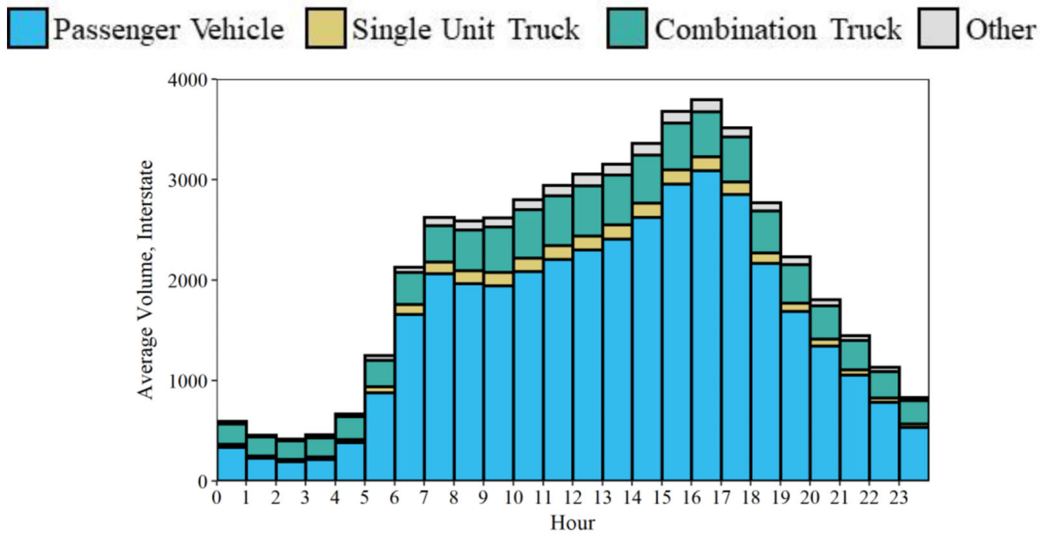
Figure 2.4 Locations of 40 count stations on Indiana roadways.

of one week between Monday, May 9th and Sunday, May 15th, 2022. An example count station located on I-65 MM 47, utilizes inductive loops shown by callout i in Figure 2.4. Out of the 40 count stations, 19 were along interstates (shown by red circles in Figure 2.4) and the remaining 21 were along non-interstate roadways (shown by blue circles in Figure 2.4) covering different geographical areas of the state. The traffic count data was grouped hourly at each location along with vehicle classification information for further analysis.

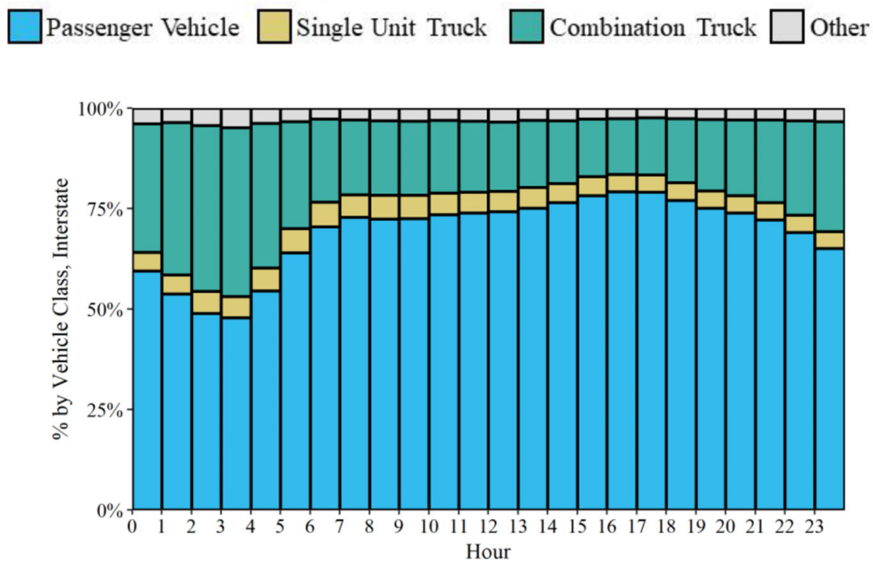
Hourly average vehicle volume (V_i^c) and hourly percentage of vehicle class (v_i^c) is shown in Figure 2.5 and Figure 2.6 for interstates and non-interstate roadways, respectively. Total hourly average volume for interstates ranged from 419 (2 AM–3 AM) to 3,801 (4 PM–5 PM). Passenger vehicles had the most volumes during all hours compared to any other vehicle class. On average, 3% of vehicles were of another type. Percent of combination trucks were higher during night hours compared to during the day. It was the highest between 2 AM and 3 AM and captured 42% of all traffic counts. During the 4-hour period from 1 AM to 5 AM, the average unique counts for combination trucks was 790 compared to 1,023 passenger vehicles. Trucks were a major part of the interstate traffic stream especially during the overnight hours. On the other hand, non-interstate traffic was mostly dominated by passenger vehicles. Combination trucks accounted most during the same early morning hour from 2 AM to 3 AM at 17% of all traffic counts.

Hourly penetration rates across all interstate and non-interstate stations were aggregated and can be seen in Figure 2.7. Figure 2.7 shows average hourly penetration for connected passenger cars and trucks on interstate (Figure 2.7(a)) and non-interstate stations (Figure 2.7(b)). On interstates, trucks improved the overall penetration of CV to over 6% throughout the day and significantly during night hours. Truck penetration peaked between 2 AM and 3 AM at 3.72% whereas passenger car penetration during this period was only 2.85%. Trucks also recorded 56.7% of the total sampled CV during this period. However, trucks were not as significant on non-interstate roadways due to lower volumes. Inclusion of connected truck data also reduced the variation in CV penetration rates over the day.

Table 2.1 summarizes the hourly penetration values for both connected passenger cars and connected trucks at interstate and non-interstate station locations. Average overall penetration of CV data on interstate



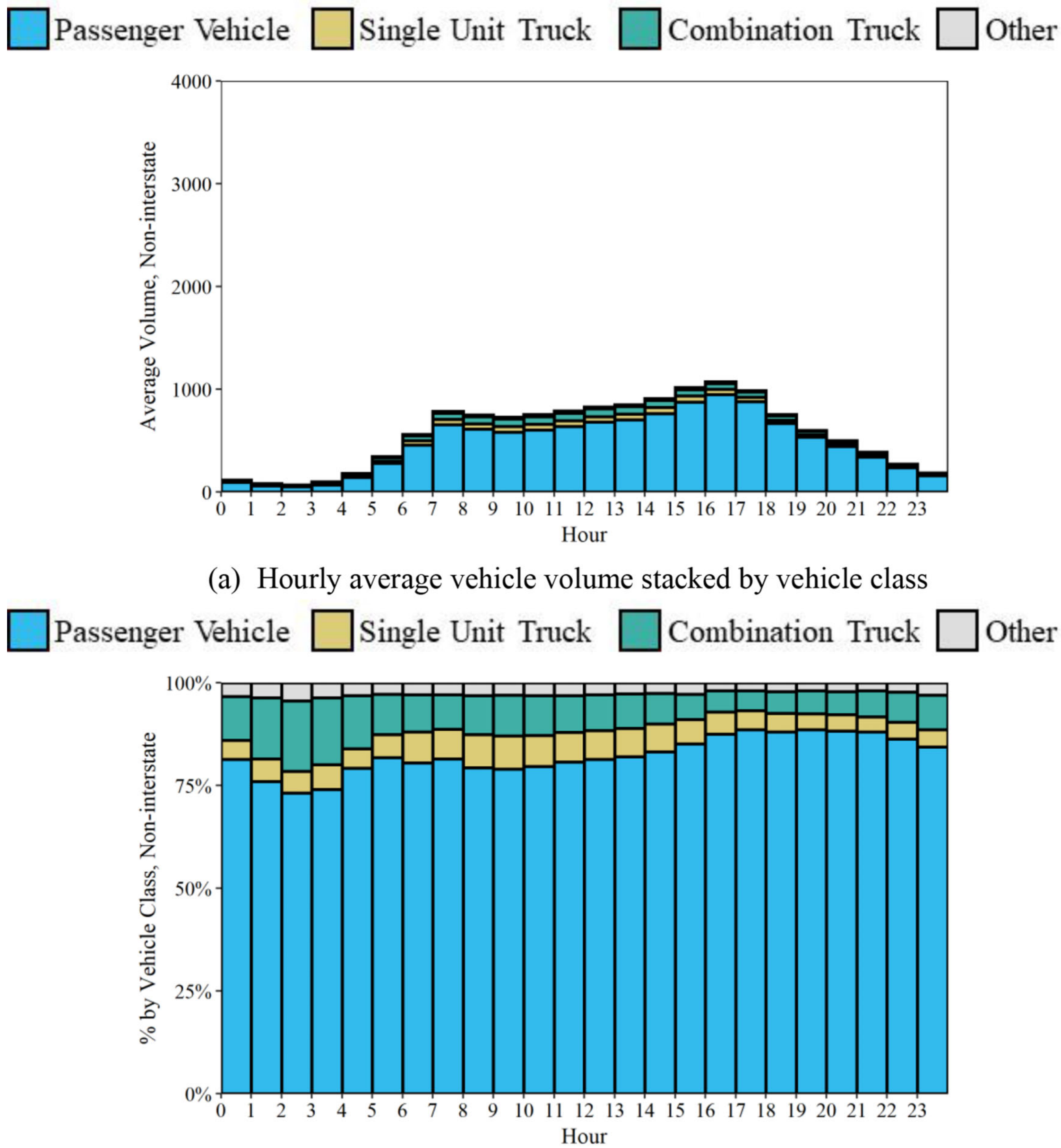
(a) Hourly average vehicle volume stacked by vehicle class



(b) Hourly vehicle volume percentage by vehicle class

Figure 2.5 Vehicle volume summary across 19 count stations along interstates.

stations was 6.32% (trucks accounting for 1.7%) and on non-interstate stations was 5.30% (trucks accounting for 0.65%). The average truck penetration was observed to be 3.4% during overnight hours between 1 AM and 5 AM when the connected passenger car penetration was at the lowest.



(a) Hourly average vehicle volume stacked by vehicle class

(b) Hourly vehicle volume percentage by vehicle class

Figure 2.6 Vehicle volume summary across 21 count stations along non-interstate roadways.

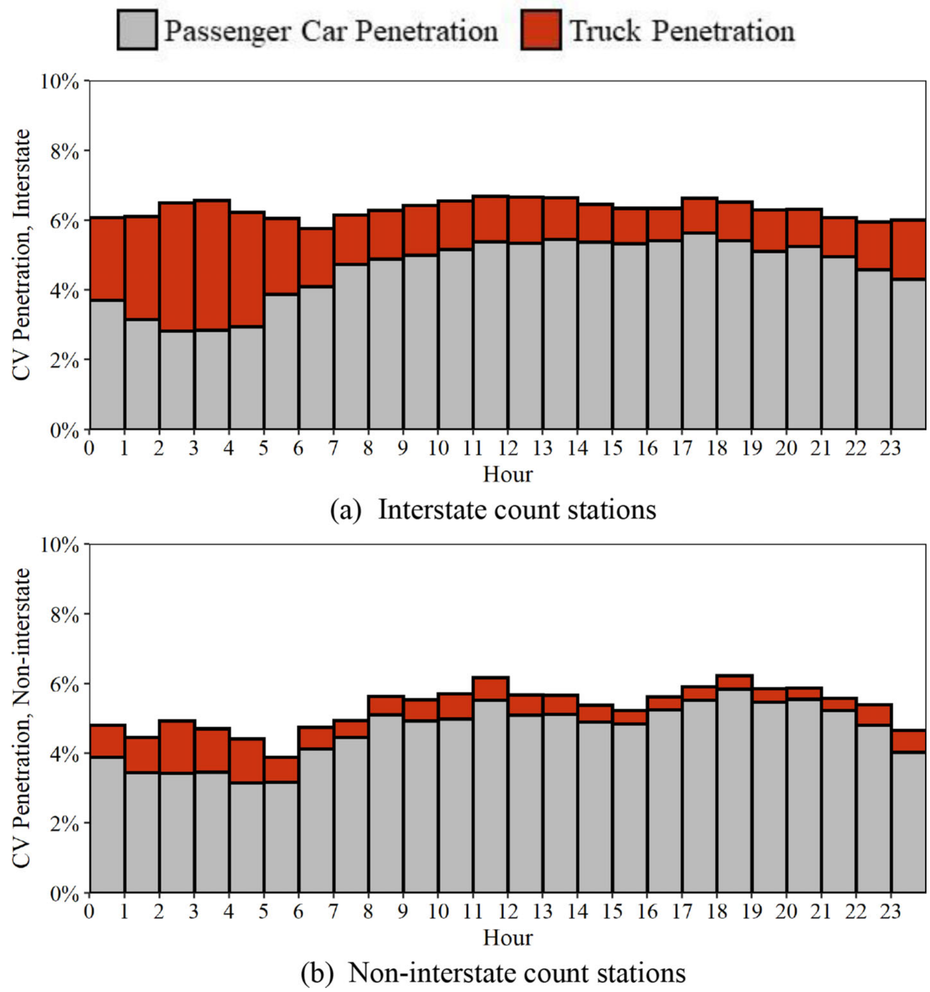


Figure 2.7 Hourly penetration of connected vehicles on interstate and non-interstate stations on Indiana roadways.

TABLE 2.1
Hourly penetration of connected passenger cars and trucks on interstate and non-interstate roadways in Indiana

	Interstate			Non-Interstate		
Hour	Connected Passenger Cars Penetration (%)	Connected Trucks Penetration (%)	Total Penetration (%)	Connected Passenger Cars Penetration (%)	Connected Trucks Penetration (%)	Total Penetration (%)
0	3.71	2.37	6.08	3.89	0.91	4.80
1	3.16	2.95	6.10	3.45	1.01	4.46
2	2.82	3.68	6.50	3.43	1.50	4.94
3	2.85	3.72	6.56	3.46	1.25	4.71
4	2.95	3.28	6.23	3.16	1.26	4.42
5	3.88	2.18	6.06	3.18	0.71	3.89
6	4.11	1.66	5.77	4.13	0.63	4.75
7	4.74	1.41	6.15	4.46	0.48	4.94
8	4.89	1.40	6.30	5.11	0.53	5.64
9	4.99	1.43	6.42	4.93	0.61	5.54
10	5.17	1.39	6.56	4.99	0.71	5.70
11	5.39	1.29	6.69	5.53	0.65	6.18
12	5.34	1.32	6.66	5.10	0.58	5.68
13	5.46	1.18	6.65	5.12	0.54	5.66
14	5.37	1.09	6.46	4.90	0.48	5.39
15	5.33	1.02	6.35	4.85	0.39	5.23
16	5.41	0.94	6.35	5.26	0.37	5.62
17	5.63	1.01	6.64	5.53	0.38	5.91
18	5.42	1.10	6.53	5.84	0.40	6.24
19	5.11	1.20	6.30	5.47	0.39	5.86
20	5.25	1.06	6.32	5.55	0.32	5.87
21	4.95	1.13	6.08	5.24	0.34	5.58
22	4.58	1.37	5.95	4.81	0.60	5.40
23	4.31	1.70	6.01	4.03	0.64	4.67
Average	*4.62*	*1.70*	*6.32*	*4.64*	*0.65*	*5.30*

3. WEATHER DATA

The National Oceanic and Atmospheric Administration (NOAA) publishes High-Resolution Rapid Refresh (HRRR) weather data (Sakhare et al., 2023). HRRR provides hourly weather parameter information as 3-by-3-kilometer spatial boundaries, hereafter referred to as HRRR grid. It provides information about precipitation rate or rain intensity, temperature conditions, visibility, wind speeds, and solar flux values along with timestamp and location identification. Table 3.1 shows the rain categorization as laid out by United States Geological Survey (USGS) (USGS, n.d.) based on precipitation rate values.

3.1 Case Study Along I-65

Figure 3.1 shows a qualitative example of impact of precipitation rate observed from HRRR data on traffic speeds along I-65 on July 7th, 2022. Figure 3.1a and Figure 3.1b shows a spatial-temporal heatmap of traffic speed from CV data color-coded by speed bins for 55 miles of I-65 from MM 115 to MM 170 for northbound (NB) and southbound (SB), respectively. The horizontal axis represents the time of the day and vertical axis shows the mile marker location. The direction of the arrow next to vertical axis represents the direction of travel. Figure 3.1c shows the precipitation rate from HRRR data provided with temporal resolution of one hour. The storm moved SB starting around 6:00 AM in the morning near MM 170 and reached MM 115 after 6 hours around noon. It can be estimated that the storm was moving SB at speed of around 9 mph. Traffic speeds were observed to be impacted in orange (35 to 44 mph) and in red (25 to 34 mph) in both NB and SB directions (Sakhare, Desai, Li, et al., 2021). However, it can be seen that traffic in SB direction (Figure 3.1b) had greater impact compared to NB (Figure 3.1a).

TABLE 3.1
Categorization of precipitation rate shown by USGS

Rain Category	Precipitation Rate (mm/hour)
No Rain	0
Slight Rain	0–0.5
Moderate Rain	0.5–4
Heavy Rain	4–8
Very Heavy Rain	>8

An hour of very heavy rain (>8 mm/hour) between 11:00 AM and noon shown by callout iii from MM 120 to MM 130 impacted SB travel severely (callout ii). However, NB traffic was less impacted (callout i). Though the rain intensities were same as it was the same stretch of the interstate, the direction of wind was opposite for SB traffic (headwind) and in the direction (tailwind) for NB traffic. Figure 3.2a to Figure 3.2c

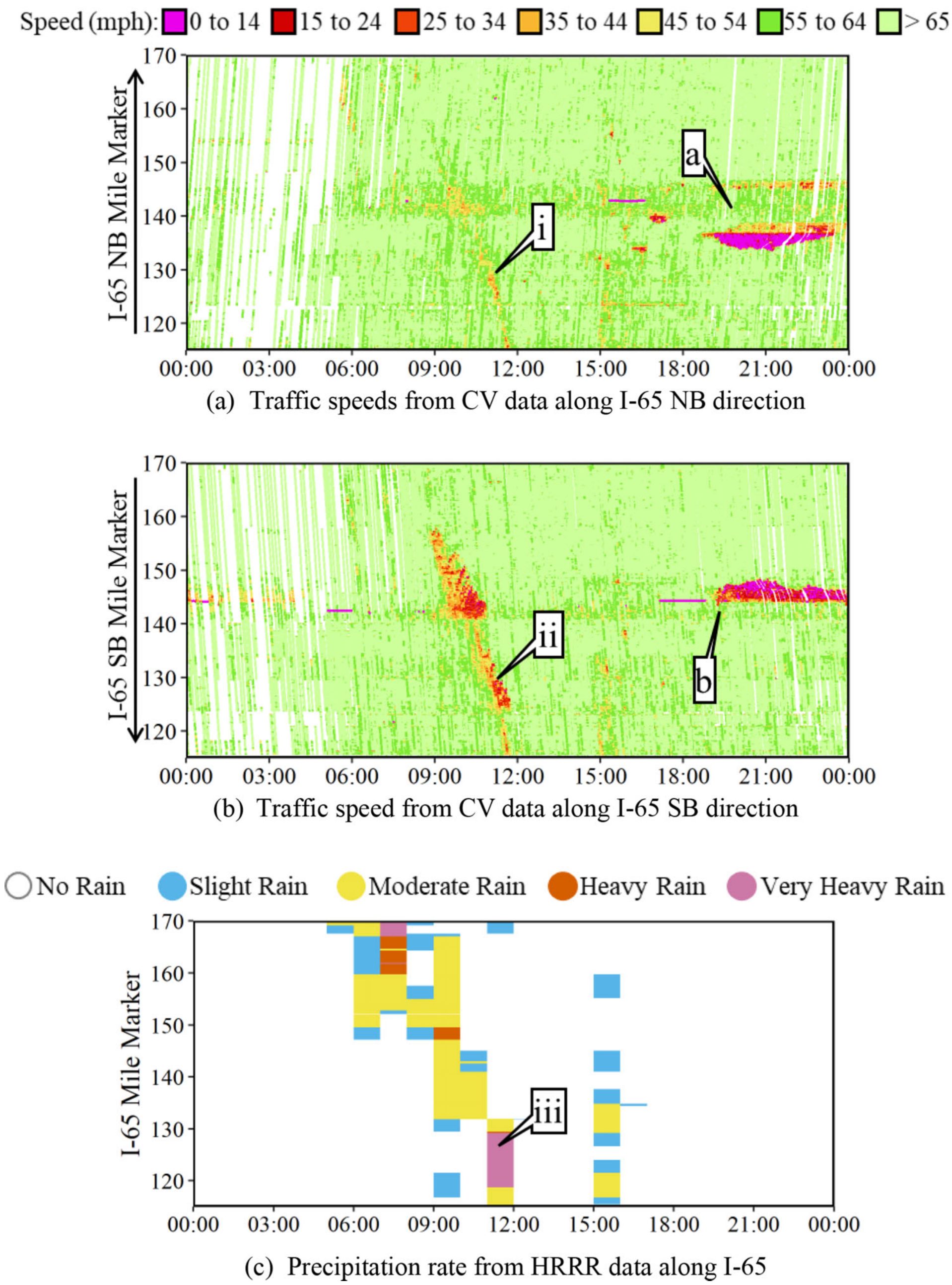


Figure 3.1 Qualitative example of the impact of rain and wind direction on traffic speeds on July 7th, 2021.

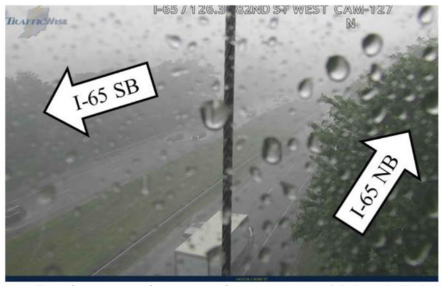
shows the road visibility from camera images at MM 126.3 during the passing of the storm.

Around MM 140, traffic speeds were observed to be congested with back-of-queue traffic in both directions of travel shown by callout a and b in Figure 3.1 due to work zone operations. The camera image at MM 138 at 7:15 PM confirms the active work zone deployment and congested traffic (callout a) shown in Figure 3.2d.

3.2 Quantitative Aggregated Analysis

Figure 3.3 shows the density and cumulative density of average speed by precipitation rate categories as defined in Table 3.1 for all 275,244 trip records. It can be clearly observed that speeds lowered (shifted to the left) with increasing rain intensity category. Vertical dotted lines shown in Figure 3.3a represent means for the respective category. The density distribution was left-skewed for all categories. Horizontal lines in Figure 3.3b show first quartile (25th percentile), second quartile/median (50th percentile) and third quartile (75th percentile), respectively, from bottom to top. Cumulative distribution shows wider gap at first quartile but tighter fit at third quartile between the categories indicating an extended lower speed tail for higher precipitation rate categories due to driver behavior variability in inclement conditions.

(a) Before very heavy rain at 10:36 AM at MM 126.3



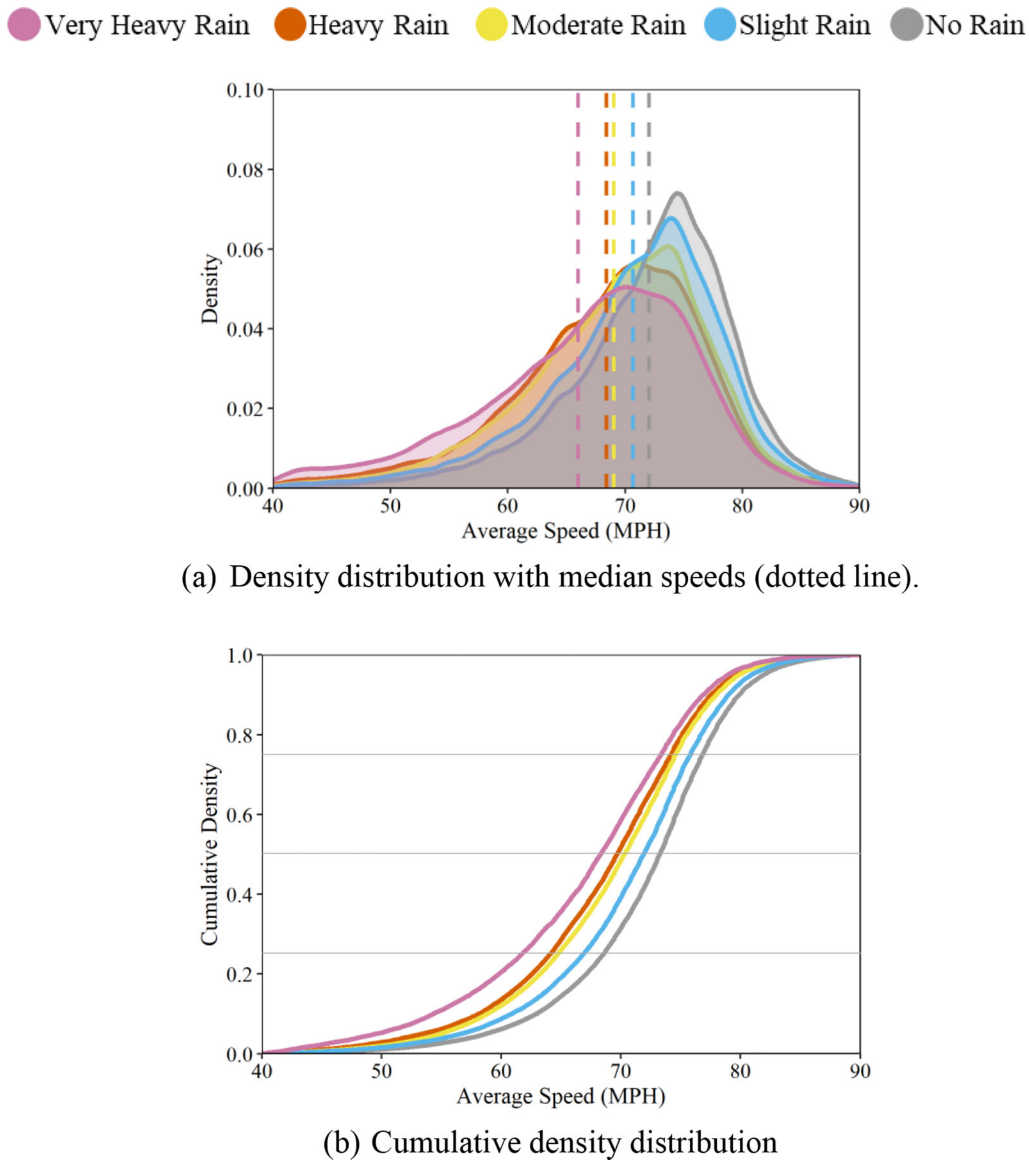
(b) During very heavy rain at 11:12 AM at MM 126.3

(c) After very heavy rain at 12:06 PM at MM 126.3

(d) Camera image of work zone operation at 7:15 PM at MM 138

Figure 3.2 ITS camera images along I-65 MM 126.3 at similar location shown by callout i, ii, and iii in Figure 2.5 and MM 138.

Table 3.2 summarizes speed statistics for each of these categories. The mean speed was 72.05 mph during no rain conditions and 66 mph in very heavy rain. It decreased by 1.93% in slight rain, 4.19% in moderate rain, 5.04% in heavy rain and 8.40% in very heavy rain conditions. Interquartile range (IQR) i.e., third quartile minus first quartile increased with increasing precipitation rate suggesting the driver speed selection during rainstorms increased in variability. Figure 3.4 shows box-whisker plot of average speeds in different rain categories. The bottom line represents 25th percentile, center line 50th percentile/median and top line 75th percentile of average speeds for each of the categories. Black dots denote mean of average speeds.



(a) Density distribution with median speeds (dotted line).

(b) Cumulative density distribution

Figure 3.3 Average speeds distribution for various precipitation rate categories.

TABLE 3.2
Summary of speed impacted by precipitation rate categories

PRATE Category	PRATE Value (mm/hour)	# Trip Records	Mean Speed (mph)	25th Percentile Speed (mph)	Median Speed (mph)	75th Percentile Speed (mph)	Interquartile Range	Percent Decrease in Average Speed (%)
No Rain	0	123,450	72.05	68.48	73.21	76.82	8.34	–
Slight Rain	0–0.5	35,243	70.66	66.77	71.86	75.79	9.02	1.93
Moderate Rain	0.5–4	107,762	69.03	64.58	70.21	74.52	9.94	4.19
Heavy Rain	4–8	20,160	68.42	63.97	69.61	74.15	10.18	5.04
Very Heavy Rain	>8	10,689	66.00	60.94	68.00	73.21	12.27	8.40

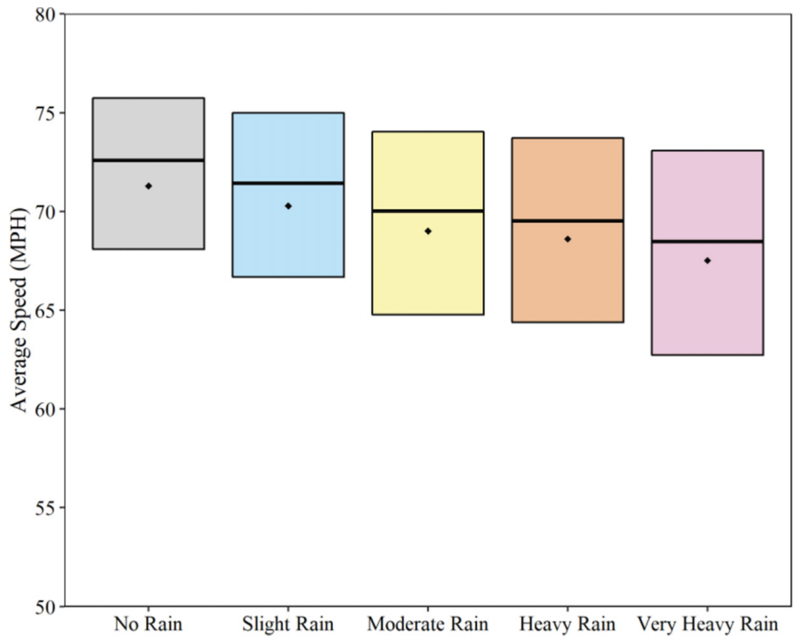


Figure 3.4 Comparison of average speeds by USGS precipitation rate categories.

4. CONNECTED VEHICLE DATA CENTRIC DASHBOARDS

A common landing page for the six different dashboard tools developed in part over the course of this project can be accessed at https://tmc-dashboards.uc.r.appspot.com, a snapshot of which is shown in Figure 4.1. A short summary of each of the dashboards and their use cases is presented in this section.

4.1 Heatmap

Spatiotemporal traffic speed heatmaps have been used extensively by various stakeholders for assessing traffic speeds in near real time as well as for after action assessment (Desai, Mathew, et al., 2022; Desai, Mathew, et al., 2023; Desai, Sakhare, et al., 2021; Sakhare, Desai, et al., 2022). This heatmap tool has in the past visualized 5-minute aggregated segment-based traffic speeds. The tool has now been updated to support 1-minute aggregated connected passenger car and connected truck trajectory data. These also show hourly precipitation rate and temperature values from NOAA's HRRR data. Appendix A shows different available heatmap views and key combinations for accessing various dataset layers.

Figure 4.2 shows a sample view of a traffic speed heatmap along I-65 MM 135 to MM 160 on Friday, January 20th, 2023. Callout i points to the "Show Shortcut Keys" tab that highlights the interaction keys and corresponding associated features such as hard braking events (B), camera location lines (L), interstate exit lines (E), weather heatmap (W), and HAAS alert plot (H). The buttons toggle between different speed data among several other shortcut keys. Callout ii points to the "Load Weather Data" tab that queries and displays the weather data for the selected section of interstate for temperature or precipitation rate values as selected from the dropdown menu next to it. Callout iii points to the "Load Crash Data" tab that downloads and displays the crash data information as populated from the statewide repository. Crash records are updated weekly with a lag of one week to allow enough time for all reports to be filed across the state. Callout iv points to the camera images shown at the bottom of the tool that are recorded every 2 minutes from more than 600 ITS cameras deployed across the state. Callout v points to the AVL camera feed, available for the state's instrumented fleet of over 1,000 snowplows, for the selected truck with camera onboard and time duration. A left click on the heatmap would show a virtual drive plot as a solid black line which can be cleared using the "V" key. A right button click anywhere on the heatmap tool would open up a separate window that points to the corresponding mile marker location on Google Maps.

4.2 Trajectory Heatmap

The trajectory heatmap tool provides users with the ability to select any two points along any roadway in Indiana to obtain real time or historical CV trips that traversed between these two points and visualize the path of each traversed trajectory, travel time, and hard braking events between the two locations (Desai, Sakhare, et al., 2021; Desai, Scholer, et al., 2022).

Figure 4.3 shows an example view of the trajectory heatmap tool for a section of I-70 WB from MM 90 to MM 120 on Saturday, August 27th, 2022. Callouts o and d point to the location of the origin and destination selected on the map, respectively. Callout i shows the cumulative hard braking events across the section of the

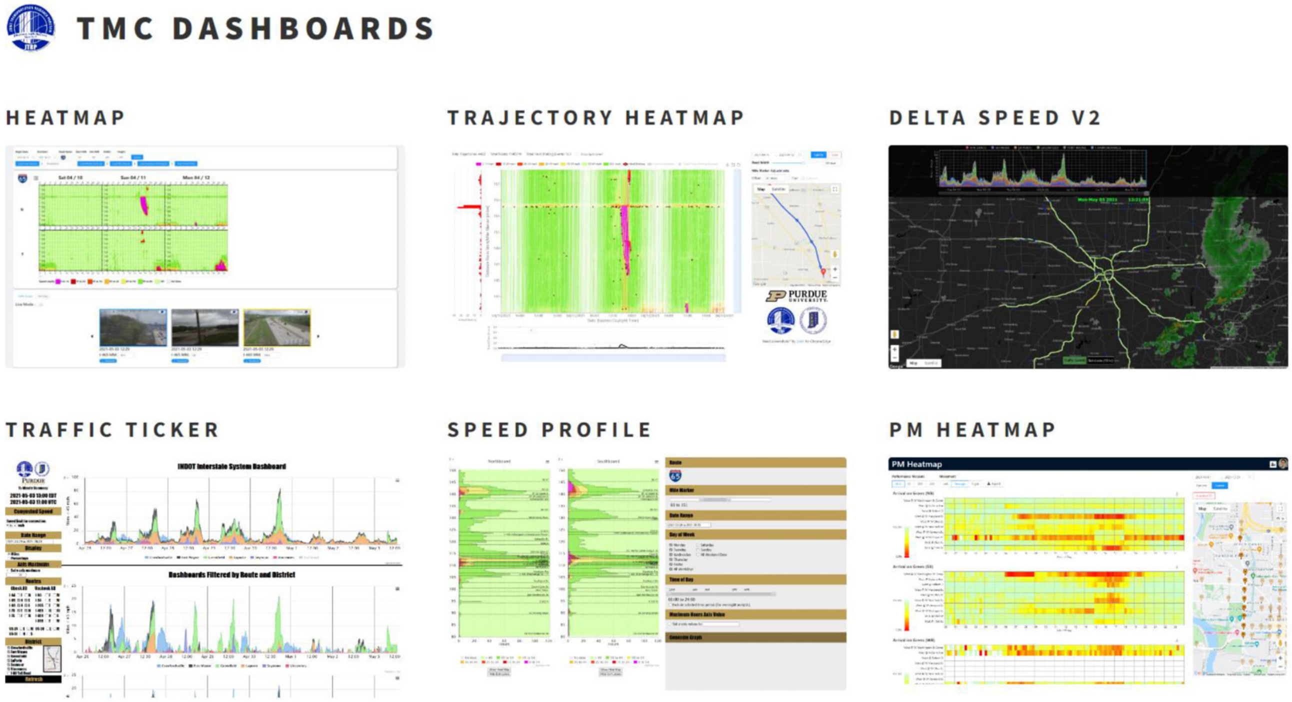


Figure 4.1 Landing page for the common view of six different dashboards.

route. Callout ii points to the travel times for each individual vehicle that passed between the origin and destination location. Average travel time is observed to be around 30 minutes for this section of the interstate and seen to rise as the motorists encountered the queue caused by an incident. Such a tool is useful for visualizing large number of trips and corresponding speeds, as well as assessing various diversions and travel time information along a corridor. This tool has proved invaluable in observing driver behavior in navigating around roadway incidents and closures due to construction, crashes or inclement weather and may potentially aid stakeholders at the local and state level in planning traffic incident management best practices and designating alternate routes.

4.3 Delta Speed V2

An earlier version of the Delta Speed Map was developed for detecting roadway incidents using measurements of differences in speeds from neighboring segments to identify where slowdowns are occurring. This was explained in detail on page 36 of the *2015 Indiana Mobility Report* (Day et al., 2016). New developments were incorporated into the Delta Speed V2 dashboard to include Doppler radar (Desai, Mahlberg, et al., 2021), AVL snowplow truck locations (Mahlberg, Desai, et al., 2022), solid and liquid application rates, automated brine application layers (Mahlberg et al., 2021), road roughness and friction data (Mahlberg, Li, et al., 2022), and HAAS alerting locations (Sakhare, Desai, Mahlberg, et al., 2021) and a district level interstate traffic ticker on top as seen from Figure 4.4. This tool provides a unified interface for visualizing a broad spectrum of datasets and helps stakeholders at the local, district and state level to monitor the impact of winter weather and corresponding winter weather maintenance operations on interstate mobility at scale.

4.4 Traffic Ticker

The default view (Figure 4.5) of the interstate traffic ticker shows system performance, specifically congested miles of interstate or miles of interstate operating below speeds of 45 mph, for the past seven days and for the entire system, however, these can be customized to show specific parts of the interstate system and time ranges. Additional details on this tool's usage and capabilities are available on page 30 of the *2015 Indiana Mobility Report* (Day et al., 2016). At a glance, this tool provides a good high-level overview of the interstate system's mobility performance, helps isolate weekday and weekend congestion trends, and elicits further investigations for non-recurring congestion events observed due to crashes and inclement weather for example.

4.5 Speed Profile

A longitudinal overview of an interstate's mobility performance is provided by the Speed Profile tool. It shows the distribution of speeds along each mile of the route over a chosen date range. Figure 4.6 shows an overview of this tool. Selections can be made based on the choice of interstate, mile marker

Figure 4.2 Traffic speed heatmap dashboard for Indiana interstates.

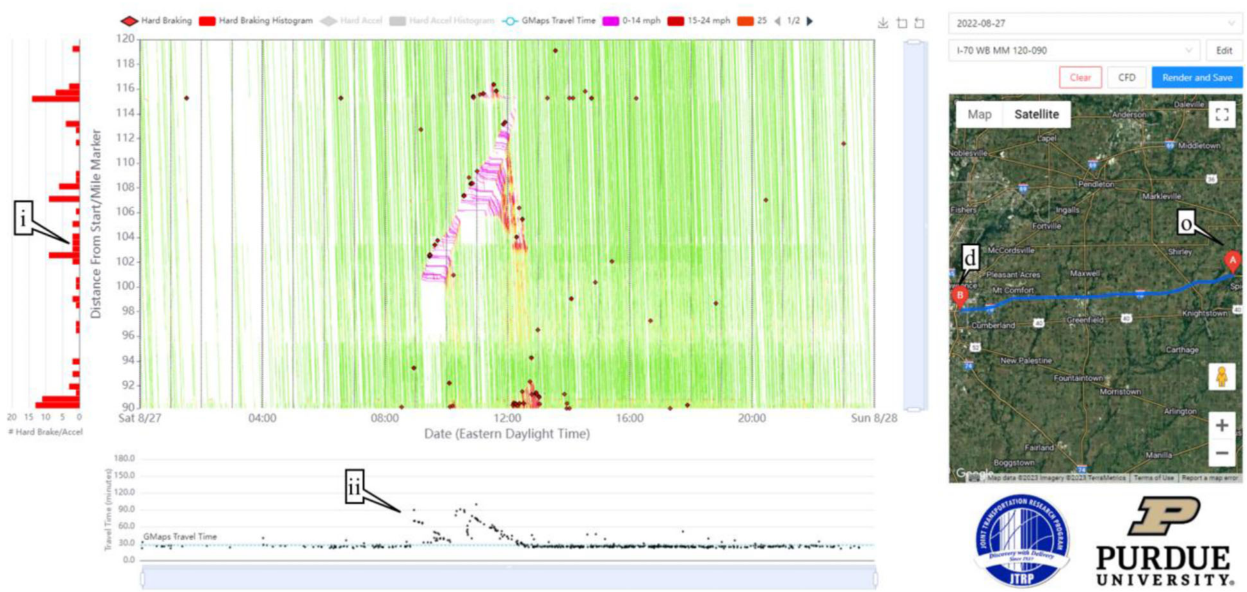


Figure 4.3 Trajectory heatmap tool example for section of I-70 WB from MM 90 to MM 120 on Saturday, August 27th, 2022.

range, date range, time of day, and day of week as seen from the right side of the window. Additional details of this tool are presented on page 35 of the *2015 Indiana Mobility Report* (Day et al., 2016). A 5-year analysis from 2018 to 2022 of monthly speed profiles for all the interstates in Indiana is presented in Appendix B (Sakhare, Li, et al., 2022).

4.6 PM Heatmap

Signal performance measures at the movement-level in terms of arrivals on green (AOG), split failures (SF), downstream blockage (DSB) and level of service (LOS) are presented in the PM heatmap tool (Figure 4.7) (Saldivar-Carranza, Li, et al., 2021; Saldivar-Carranza, Mathew, et al., 2021). Details of

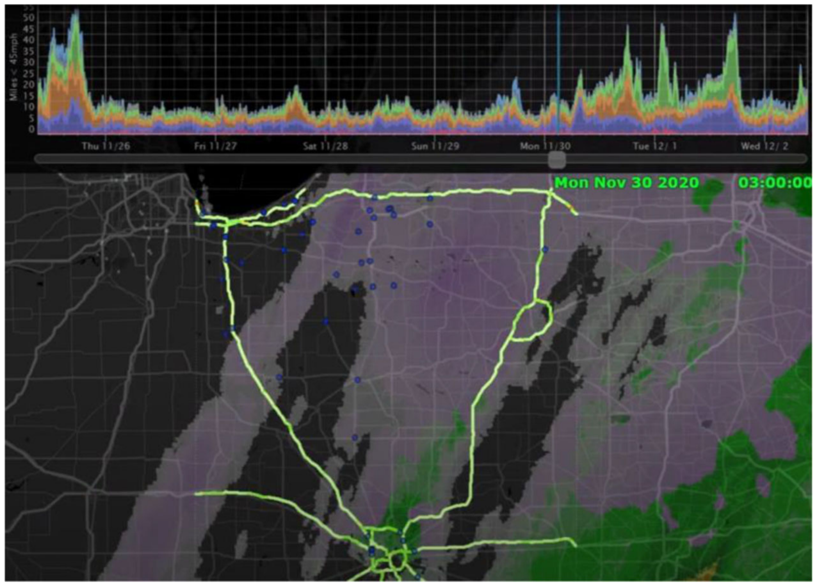


Figure 4.4 Delta speed V2 dashboard.

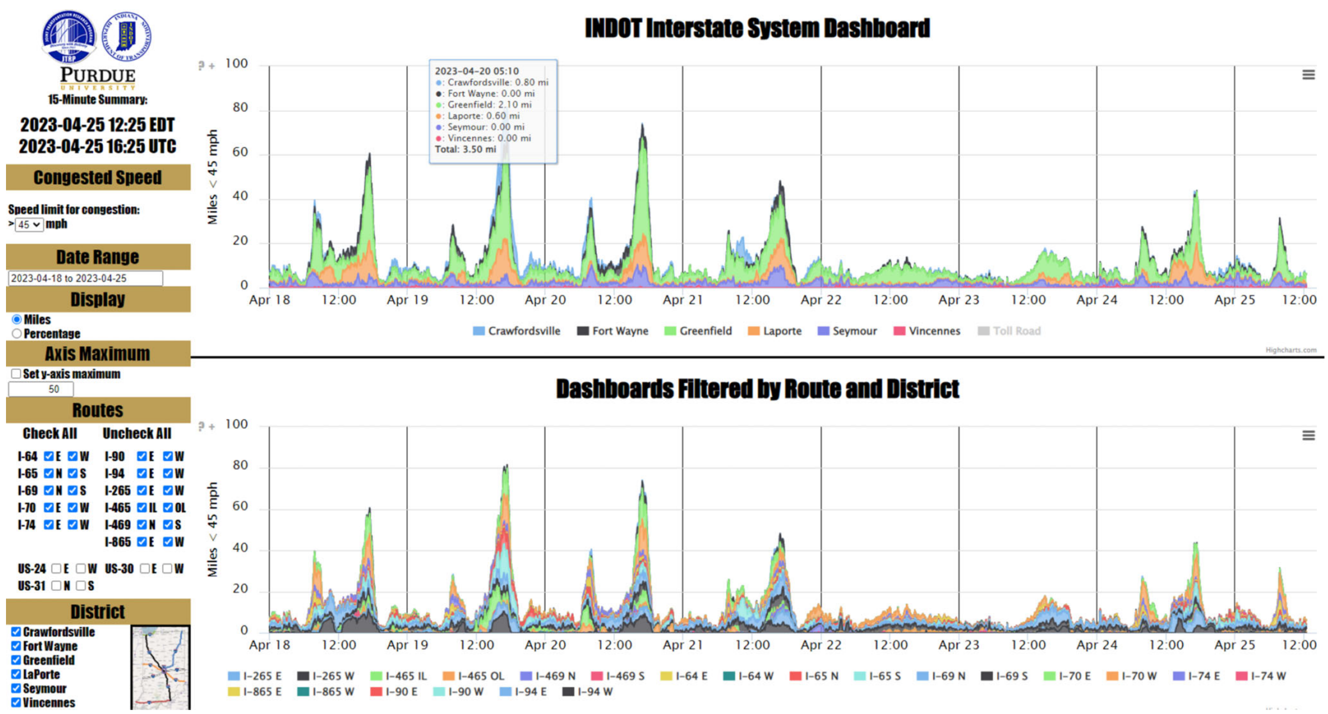


Figure 4.5 Traffic ticker dashboard.

each of the performance measures are presented in a previous report on *Integration of Probe Data Tools into TMC Operations* (Mathew et al., 2022). Almost 5,000 traffic signals located in all 50 states and Washington, D.C., are currently mapped in this tool.

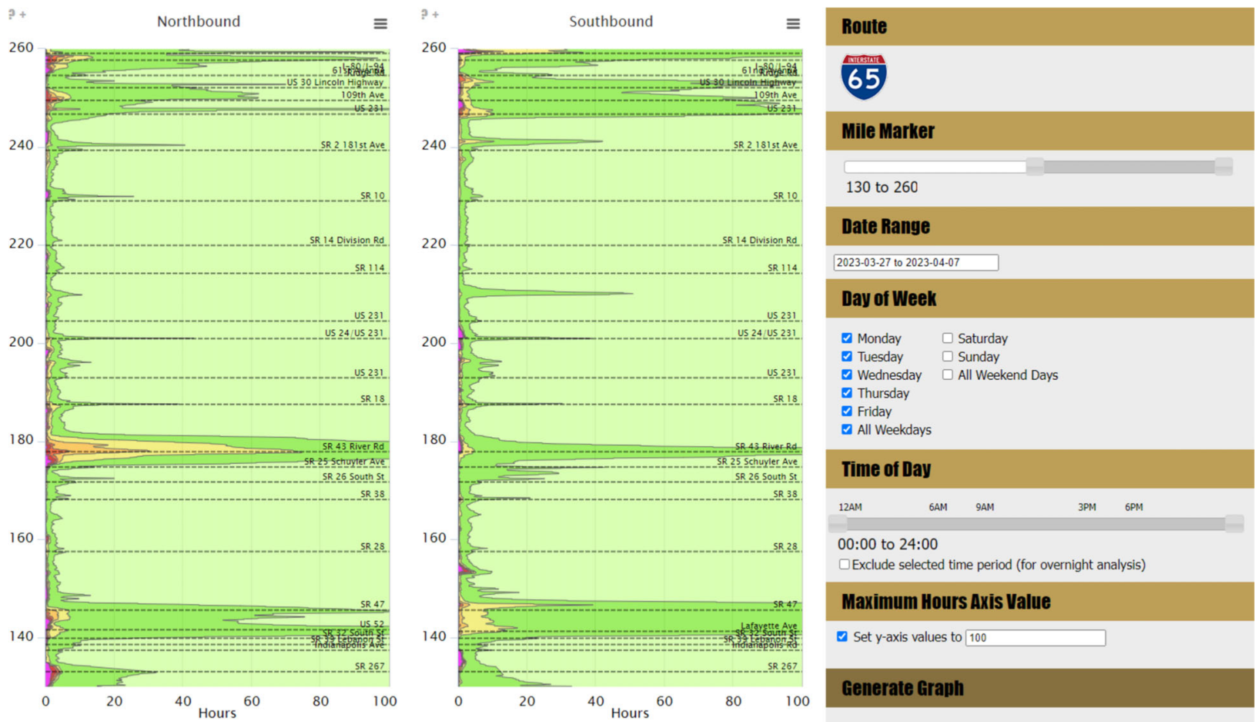


Figure 4.6 Traffic speed profiles dashboard.

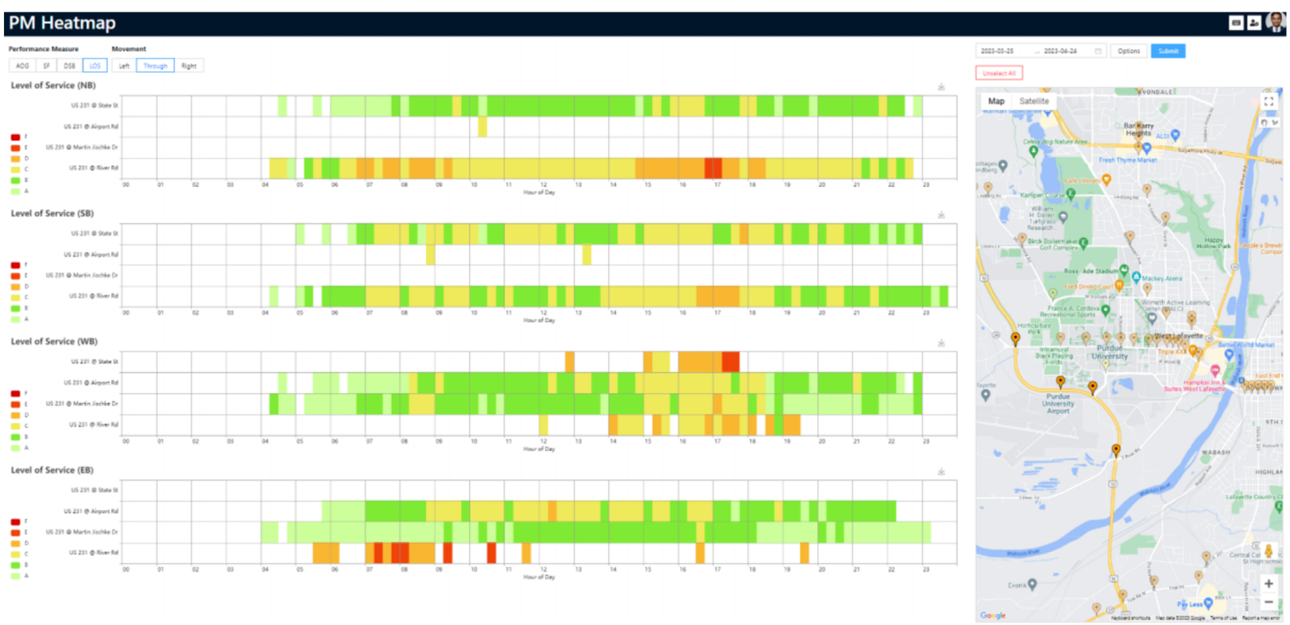


Figure 4.7 PM heatmap dashboard.

5. CASE STUDY ON IMPACT OF THE TORNADO ON THE INTERSTATE TRAFFIC

National Weather Service had reported outbreak of 23 tornadoes in Indiana on the evening of March 31st, 2023 (NOAA, 2023). This marks the fifth largest tornado outbreak in Indiana's history and the largest in central Indiana since November 17th, 2013. This case study illustrates the use of CV data and tools to assess the impact of such an event on interstate traffic in Indiana.

Figure 5.1 shows the traffic speed heatmap for the 140-mile section of I-65 both in northbound (NB) direction on the top and southbound (SB) direction at the bottom from mile marker (MM) 120 to MM 260 over duration of four days between Friday, March 31st

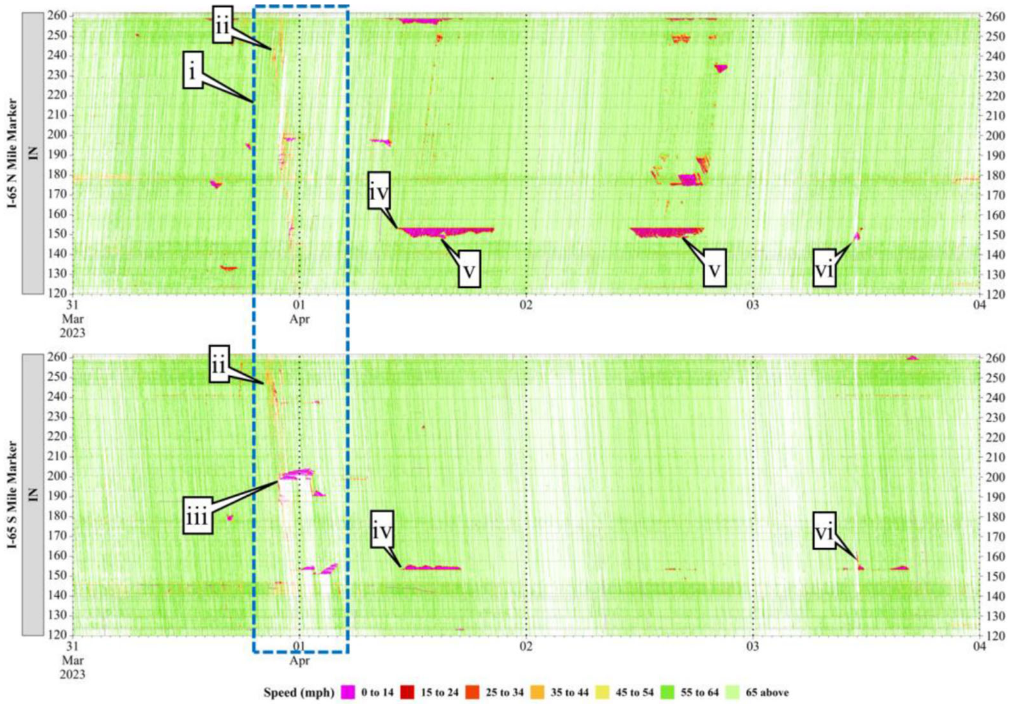
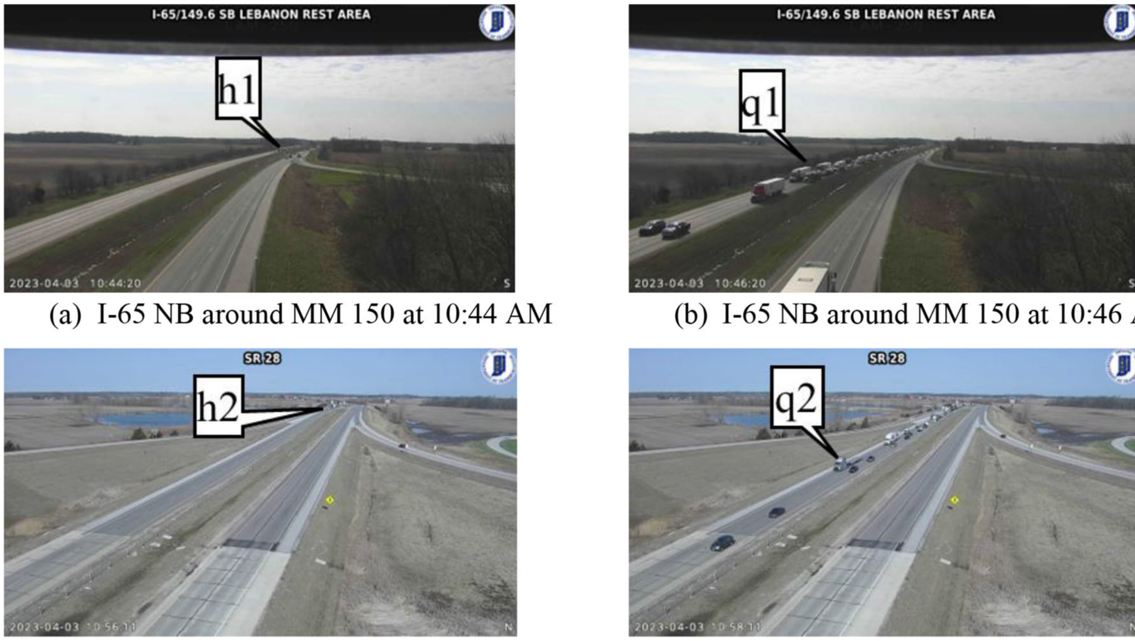


Figure 5.1 Traffic speed heatmap for section of I-65 from MM 120 to MM 260 over a duration of 4 days from Friday, March 31st to Monday, April 3rd 2023.

Figure 5.2 Debris on I-65 and slowed down traffic due to rubbernecking from motorists who slowed down to see the impact of the tornado (Tocco, 2023).

and Monday, April 3rd. Callout i, highlighted by blue dotted box points to the impact of tornado as it was moving southwards across the I-65 approximately between 9:00 PM on Friday and 3:00 AM on Saturday. Impacted traffic can be observed during this period by the change in speed bins from green to yellow or orange. Callout ii points to the tornado front. Severe winds during the storm caused the truck rollover incident around MM 199 about 10:20 PM (callout iii) in SB direction that closed the interstate for few hours. Rubbernecking was also observed during the day on Saturday (callout iv) and Sunday as motorists were slowing down for the debris on the interstate. Figure 5.2 shows the images of slowed traffic on the interstate and debris deposited from a nearby site that was impacted by the storms. The queue formed due to these slowdowns resulted in two back-of-queue incidents highlighted by callout v.

Rolling slowdown operations were performed in both directions on Monday for clearing the debris on and around the interstate, highlighted by callout vi. The impact due to these operations was further analyzed. Integrated camera images from the heatmap tool show the movement of the queue formed due to the rolling slowdown. Camera images were available for two camera locations at exit mile marker 150 and 158. Figure 5.3 shows consecutive camera images at 2-minute intervals from both these locations. The front or head of the rolling slowdown in the NB direction is shown by callout h1 (Figure 5.3a) and two minutes later queue (callout q1 on Figure 5.3b) passing through formed behind the rolling slowdown operation. Similar



(a) I-65 NB around MM 150 at 10:44 AM (b) I-65 NB around MM 150 at 10:46 AM

(c) I-65 SB around MM 158 at 10:56 AM (d) I-65 SB around MM 158 at 10:58 AM

Figure 5.3 Camera images 2-minutes apart during rolling slowdown operation on Monday, April 3rd along I-65 in both northbound (NB) and southbound (SB) direction.

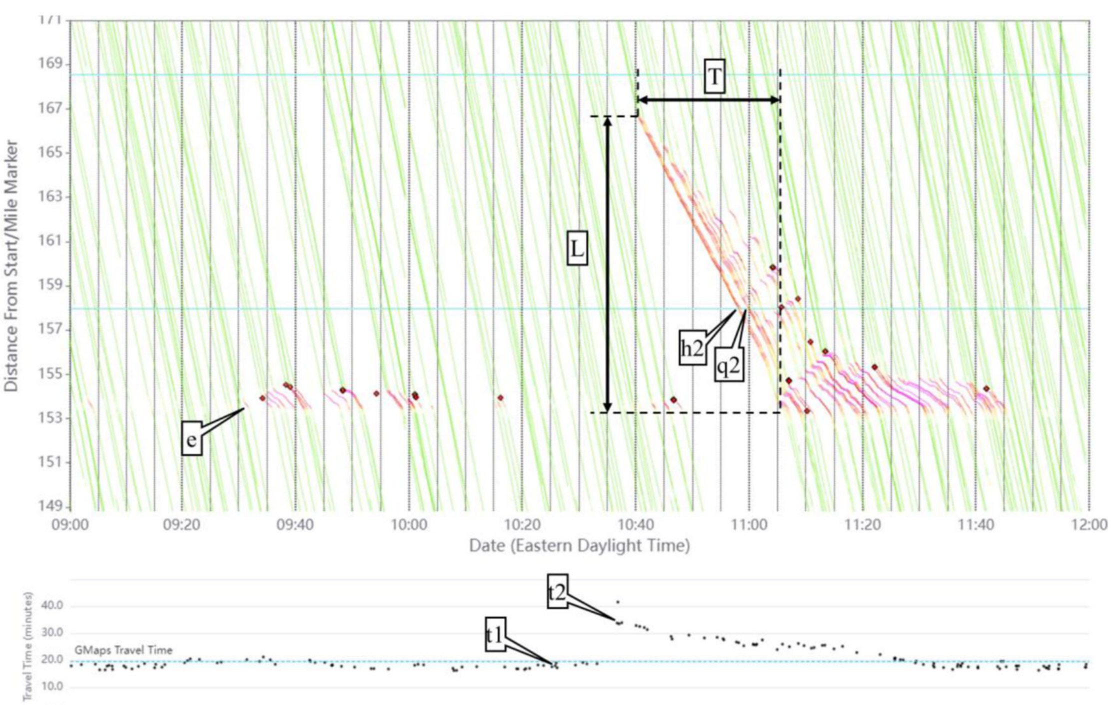


Figure 5.4 Traffic speed heatmap during rolling slowdown in I-65 SB direction on Monday, April 3rd.

operation was conducted in SB direction as well. Callout h2 (Figure 5.3c) and callout q2 (Figure 5.3d) corresponds to the head and queue during this rolling slowdown operation. Trajectory heatmap for this section of interstate from MM 149 to MM 171 is shown in Figure 5.4.

Callout e in Figure 5.4 points to the location along the interstate where traffic was slowing down due to debris on and around the interstate and some ongoing cleaning operation. Callout h2 and q2 refers to the location and time on heatmap corresponding to the images shown in Figure 5.3a and Figure 5.3b, respectively. The rolling slowdown lasted for about 25 minutes starting at 10:40 AM and finishing at 11:05 AM, denoted by callout T. The operation also was conducted for about 13 miles from MM 167 to MM 154, denoted by callout L. The estimated speed for the lead vehicle was about 31 mph. The usual travel time through this section of 22 miles was about 19 minutes (callout t1) which increased to as high as 33 minutes (callout t2) behind the slowdown.

Figure 5.5 shows the camera images from an AVL truck dash cam at MM 154 (callout e in Figure 5.4). It can be observed that truck with traffic cones getting on the scene (callout c) and maintenance workers (callout r) gathering the debris (callout d) in the

(a) 10:57 AM (b) 10:58 PM

(c) 10:59 AM (d) 11:00 AM

(e) 11:03 AM (f) 11:04 AM

(g) 11:07 AM (h) 11:08 AM

Figure 5.5 Camera images from AVL truck.

right-of-way. Initial images up until 11:03 AM (Figure 5.5a–d) show no traffic on the interstate (callout N). This was due to the rolling slowdown operation upstream of this location. Figure 5.5e–h shows flowing traffic at this location also confirmed from the trajectories in Figure 5.4 at the same location after 11:03 AM. Since the cleaning operation was still in progress as seen from the camera images in Figure 5.5e–h, queue of about 2–3 miles from the rolling slowdown did not dissipate immediately and seen slowdowns until 11:45 AM.

Overall, the CV data and associated tools were able to showcase the impact of a tornado on traffic. Wide range of assessments such as areas of slowdowns, impacts from crashes, queues formed from rubbernecking, back-of-queue crashes, rolling slowdowns and resiliency of the agency to such events were possible through these tools to aid and support their operations.

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APPENDICES

Appendix A. Integration of Aggregated CV Data Into the Traffic Speed Heatmap Tool

Appendix B. Indiana Interstate Speed Profiles

APPENDIX A. INTEGRATION OF AGGREGATED CV DATA INTO THE TRAFFIC SPEED HEATMAP TOOL

The previous data layer of 5-minute aggregated segment speed data on traffic heatmap is now overlaid with 1-minute aggregated car and truck trajectory data. Each of these layers can be turned on or off and an example is shown below along interstate I-465 using different combinations of these datasets and associated visualizations of the heatmap tool.

A.1 Default view (Keys F, D, and T Turned On)

1-minute aggregated truck trajectory data (key T) overlaid on top of 1-minute aggregated passenger car trajectory data (key D) overlaid on top of 5-minute aggregated segment-based traffic speeds (key F).

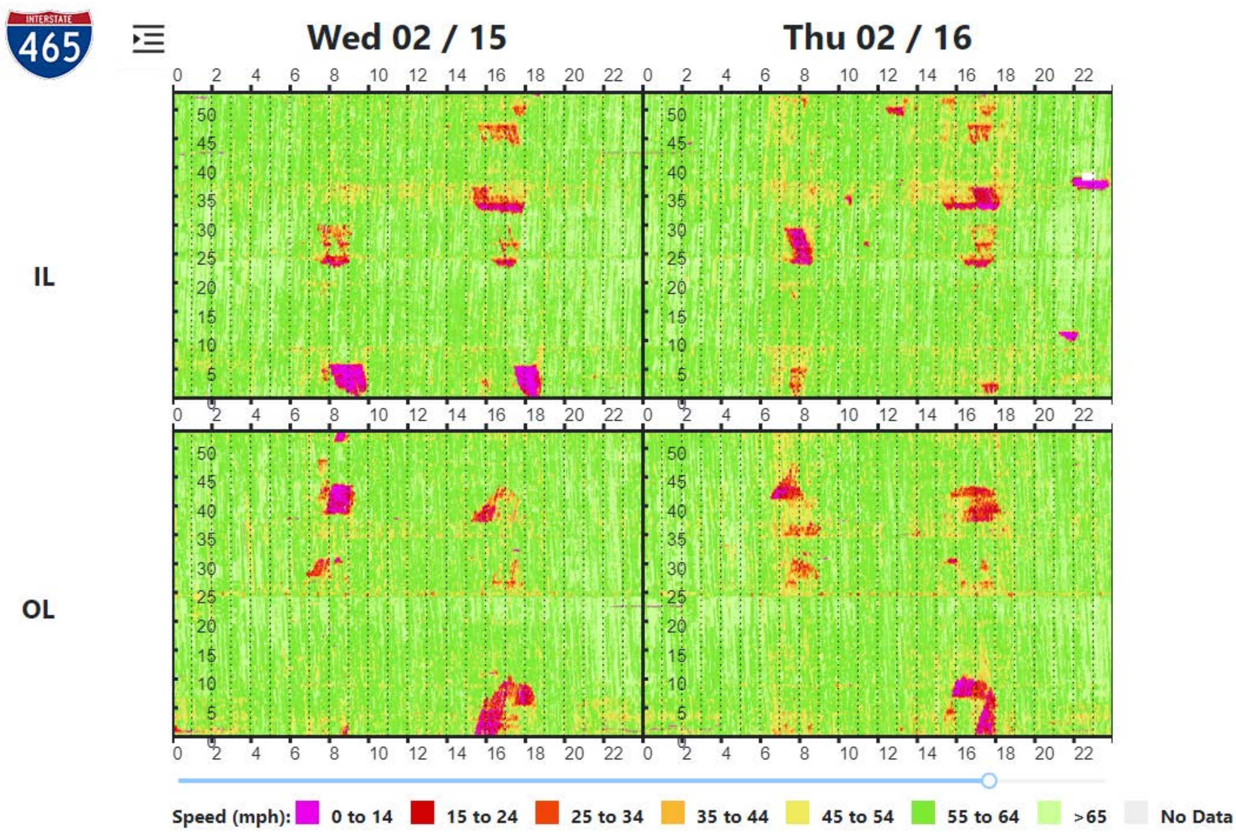


Figure A.1 Default view of heatmap tool.

A.2 Only Key F Turned On

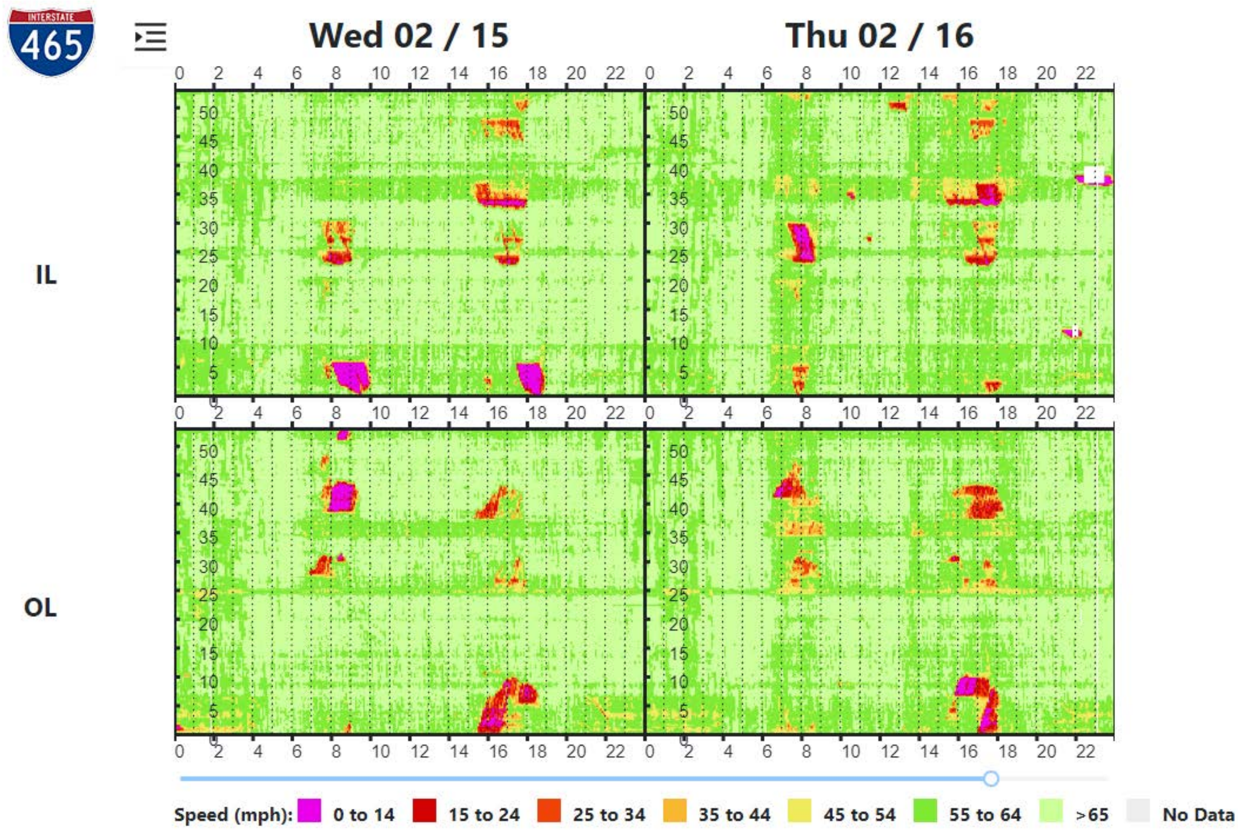


Figure A.2 Five-minute aggregated segment-based traffic speeds (key F).

A.3 Only Key D Turned On

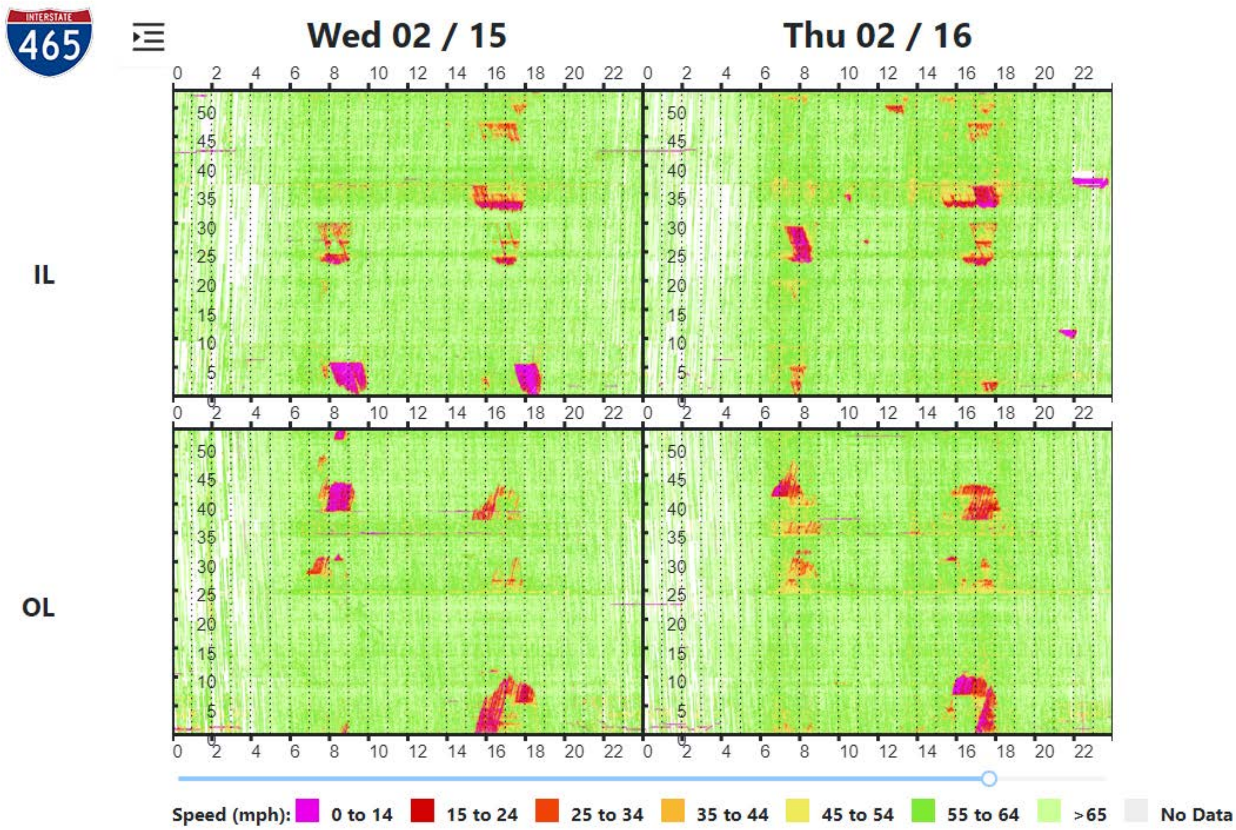


Figure A.3 One-minute aggregated passenger car trajectory data (key D).

A.4 Only Key T Turned On

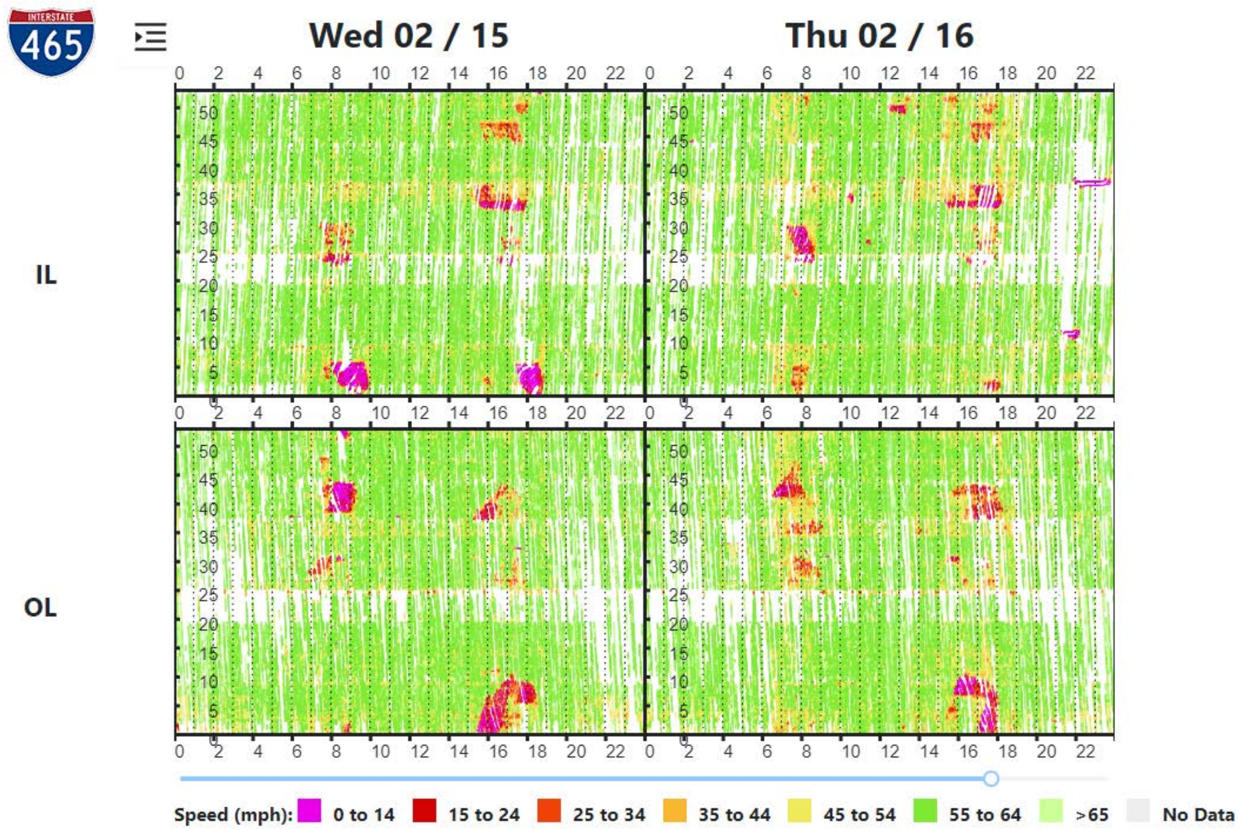


Figure A.4 One-minute aggregated truck trajectory data (key T).

A.5 Keys D and T Turned On

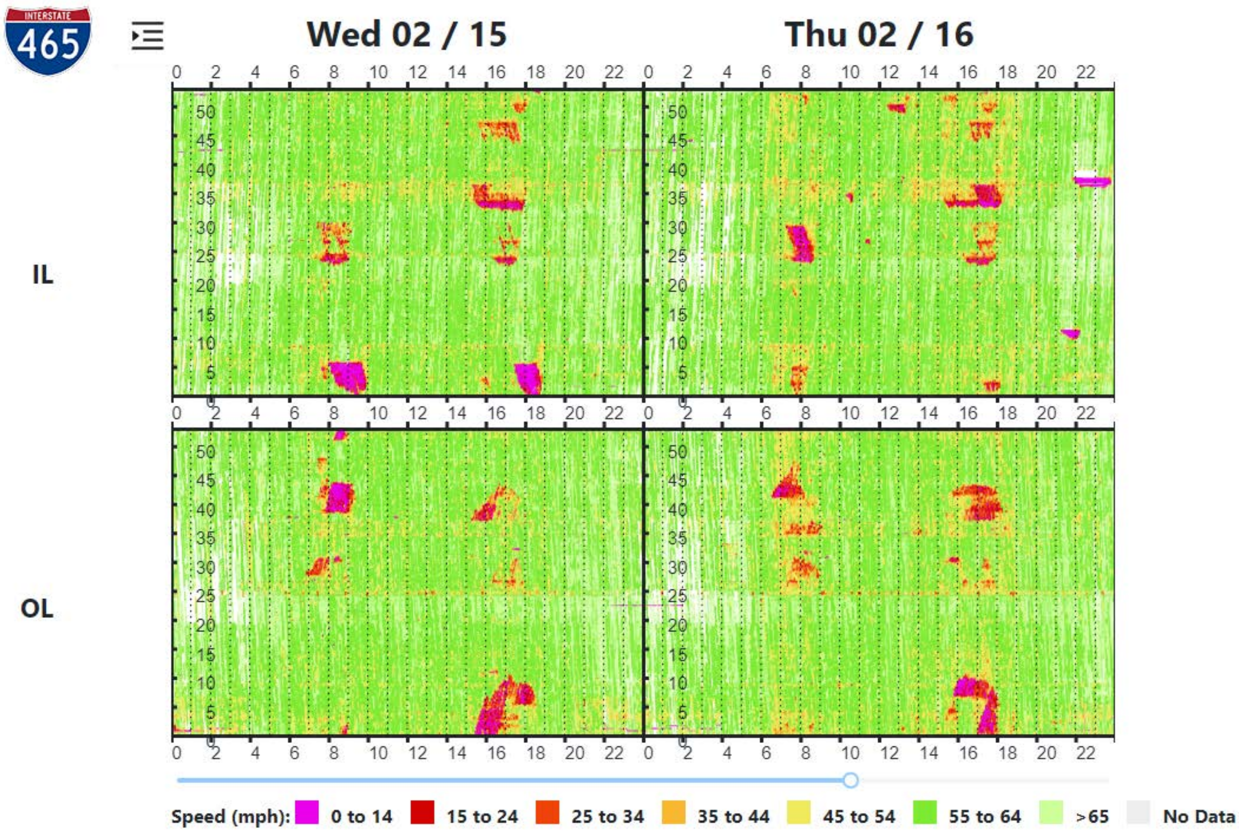
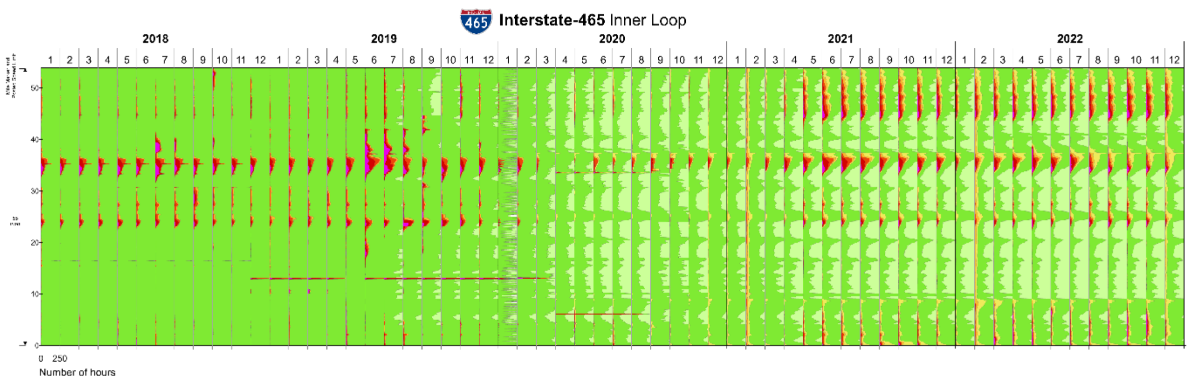


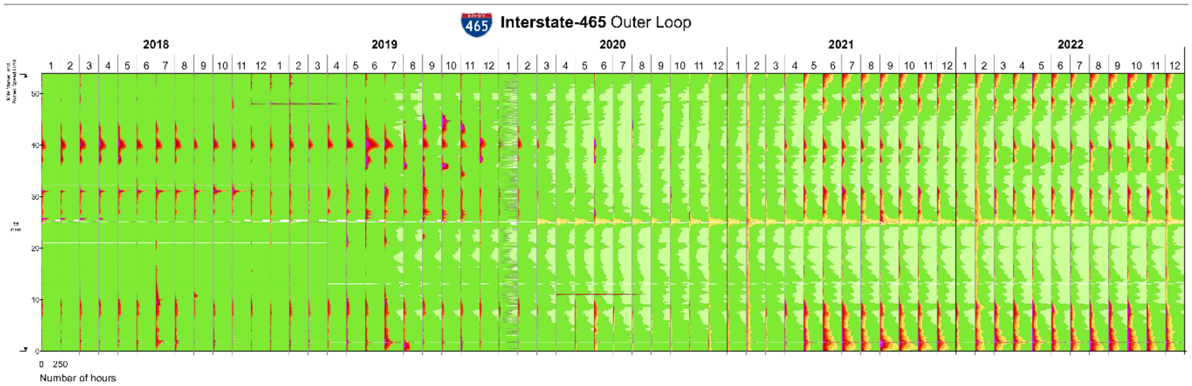
Figure A.5 One-minute aggregated truck trajectory data (key T) overlaid on top of 1-minute aggregated passenger car trajectory data (key D).

APPENDIX B. INDIANA INTERSTATE SPEED PROFILES

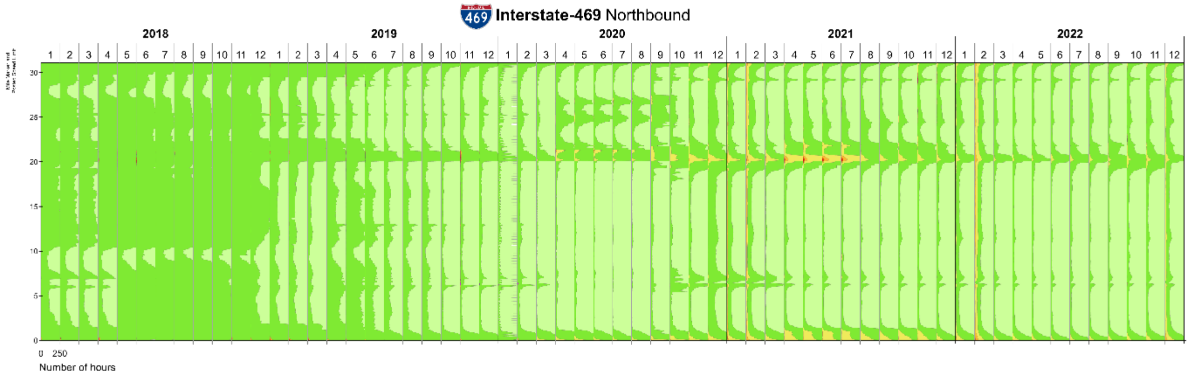
Systemwide interstate performance measures that detail the number of hours and location of congestion provide important information for decision makers to plan capital projects and assess work zone operations. Mobility report on Indiana Interstate Speed Profiles 2018-2022 (*7*) present details of these profiles.

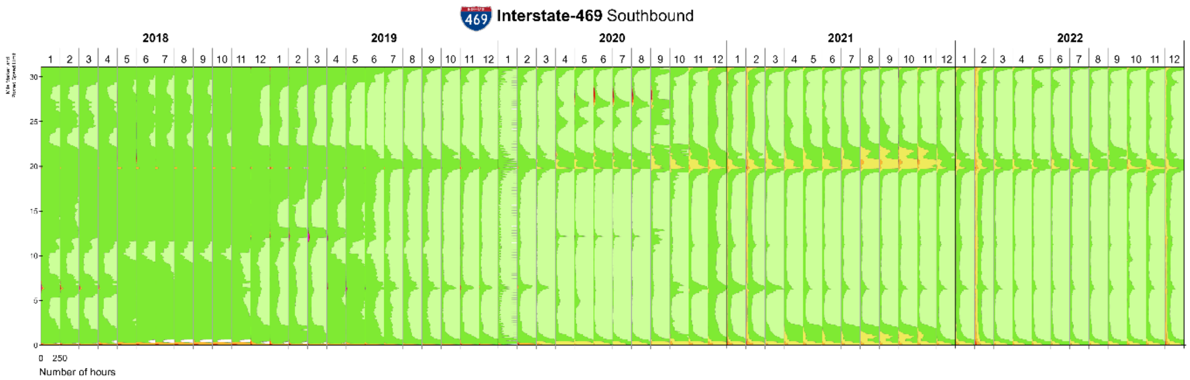
B.1 Interstate 465



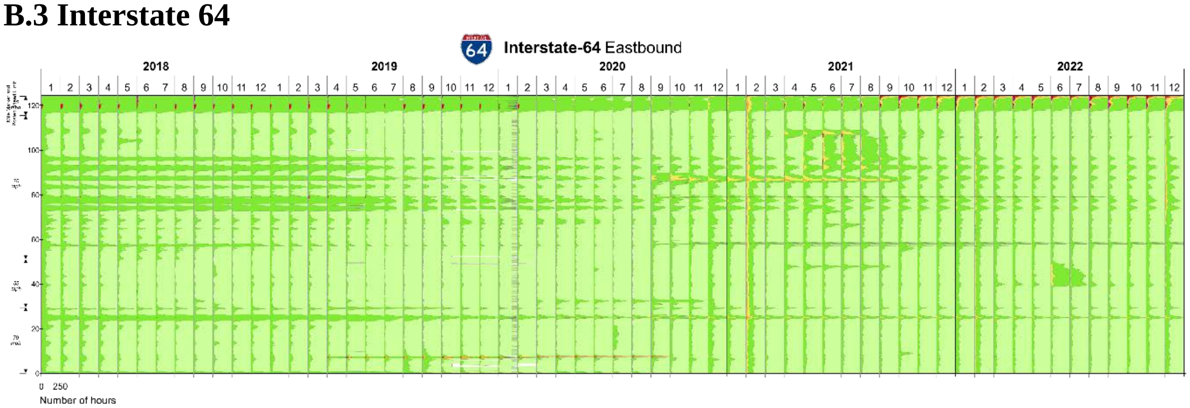


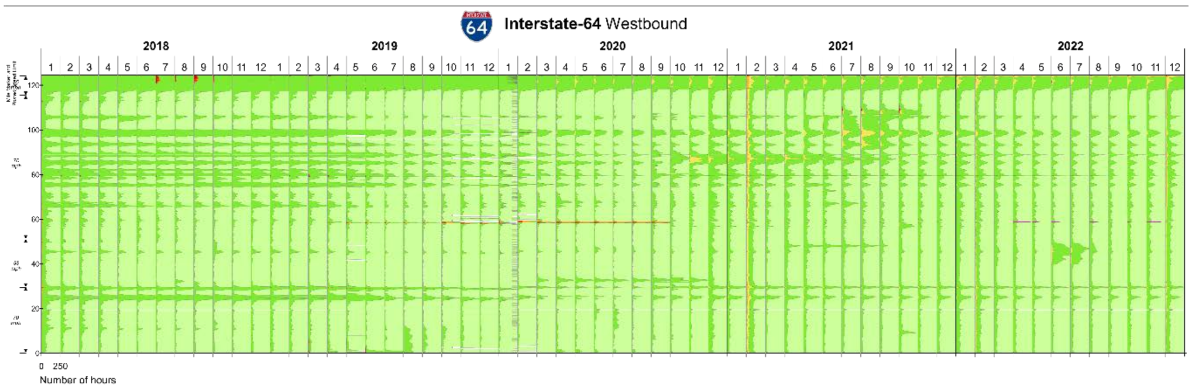
B.2 Interstate 469





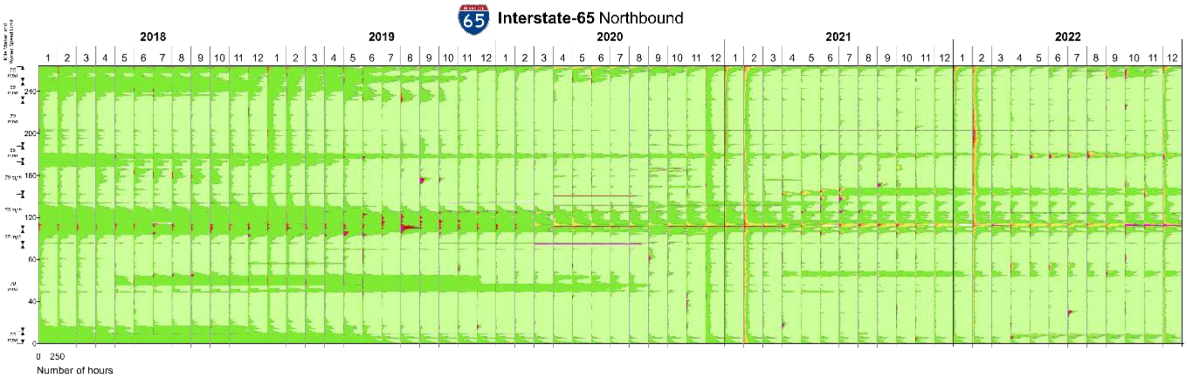
B.3 Interstate 64



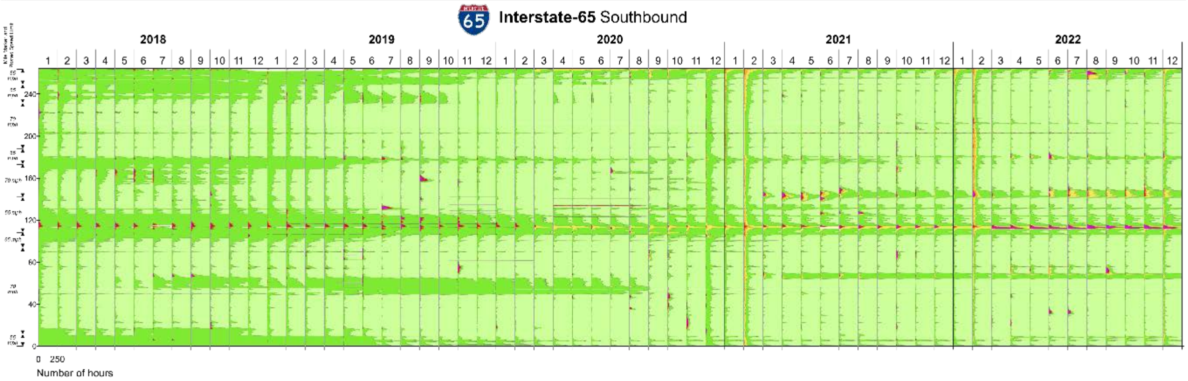


B.4 Interstate 65

Interstate-65 Northbound

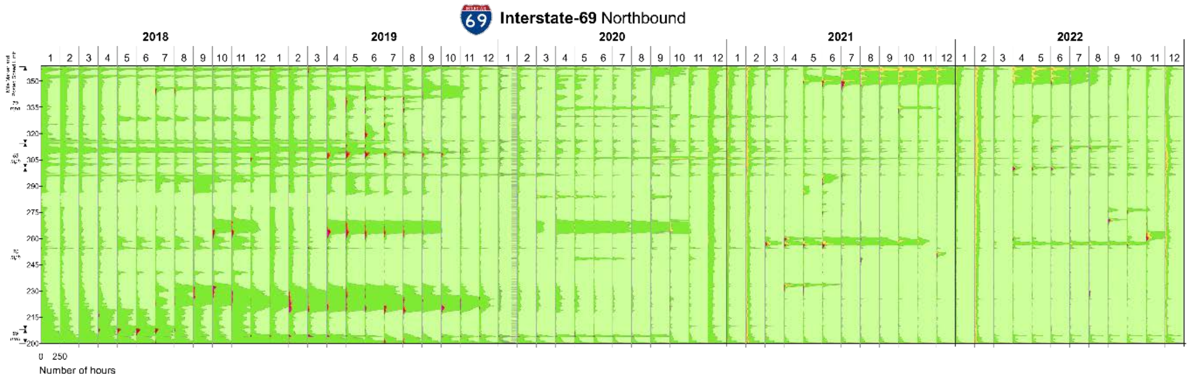


Interstate-65 Southbound

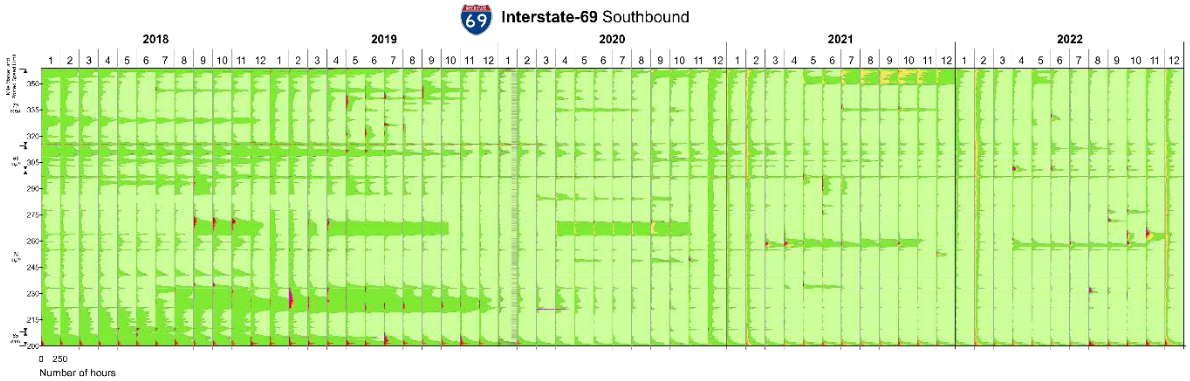


B.5 Interstate 69

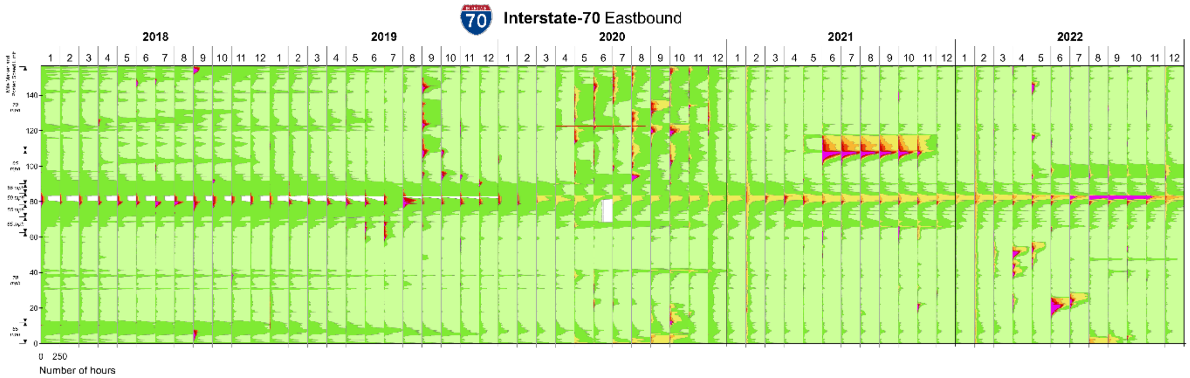
Interstate-69 Northbound

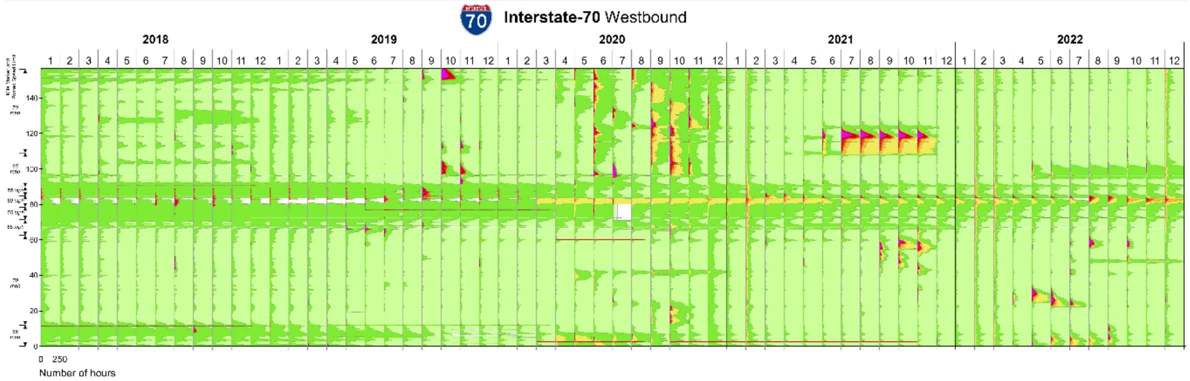


Interstate-69 Southbound

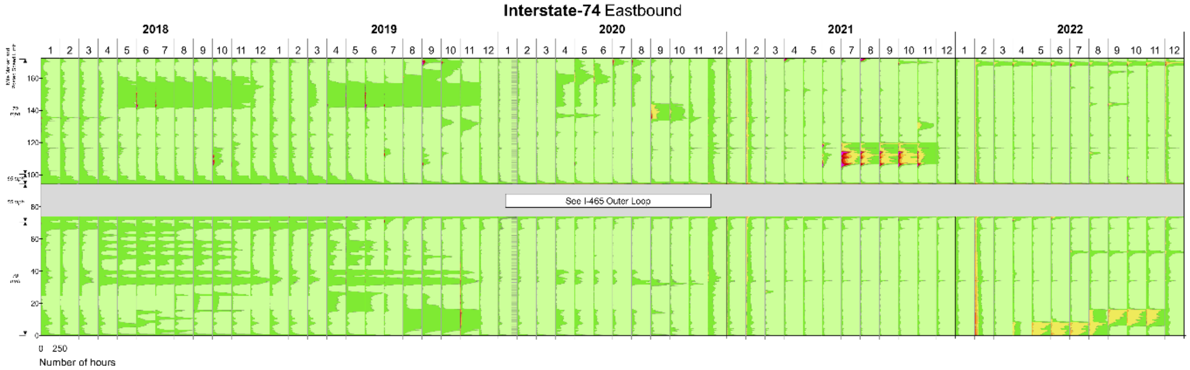


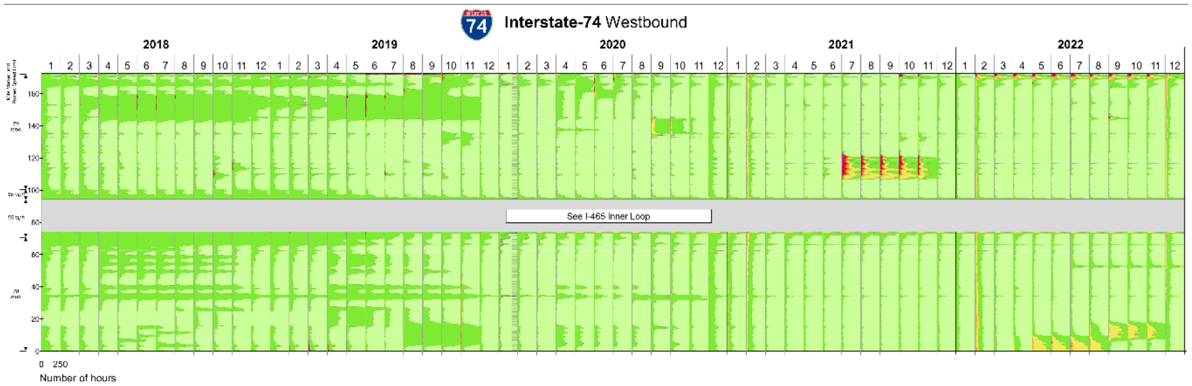
B.6 Interstate 70



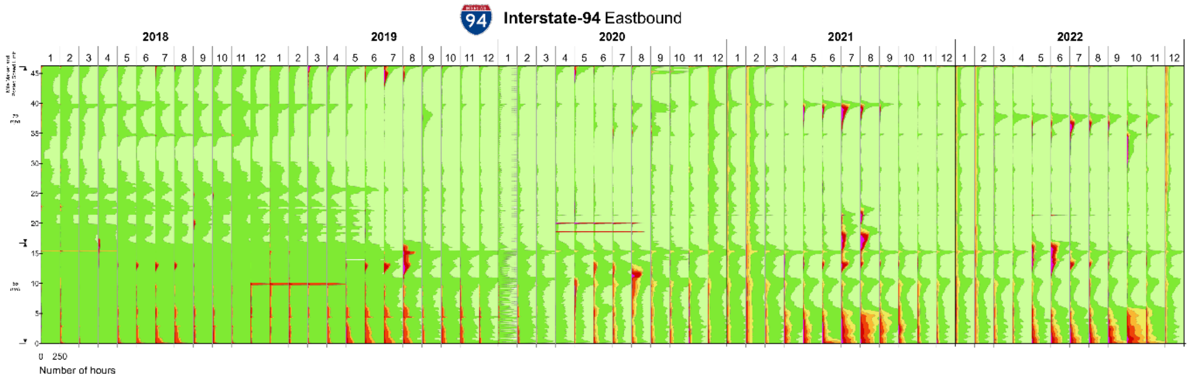


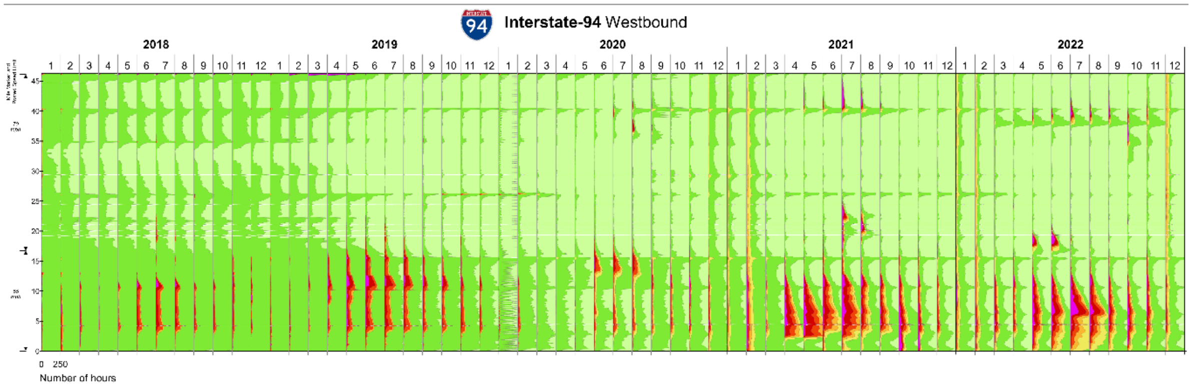
B.7 Interstate 74



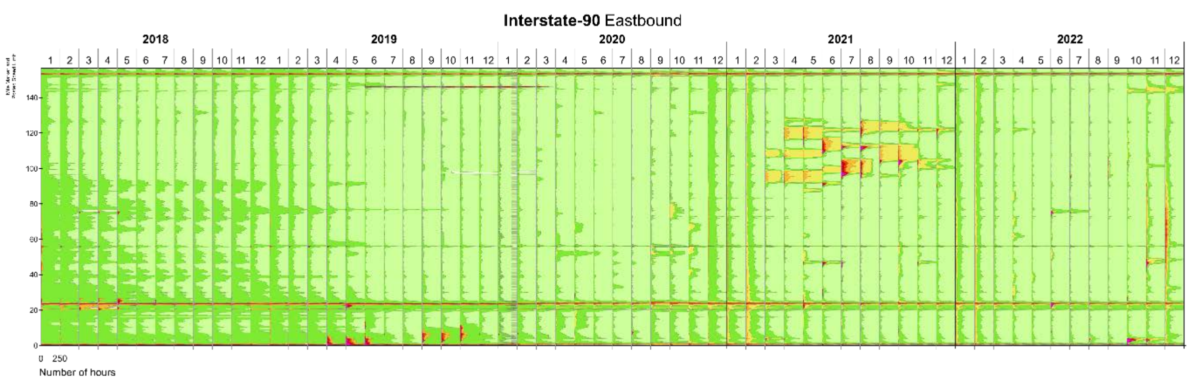


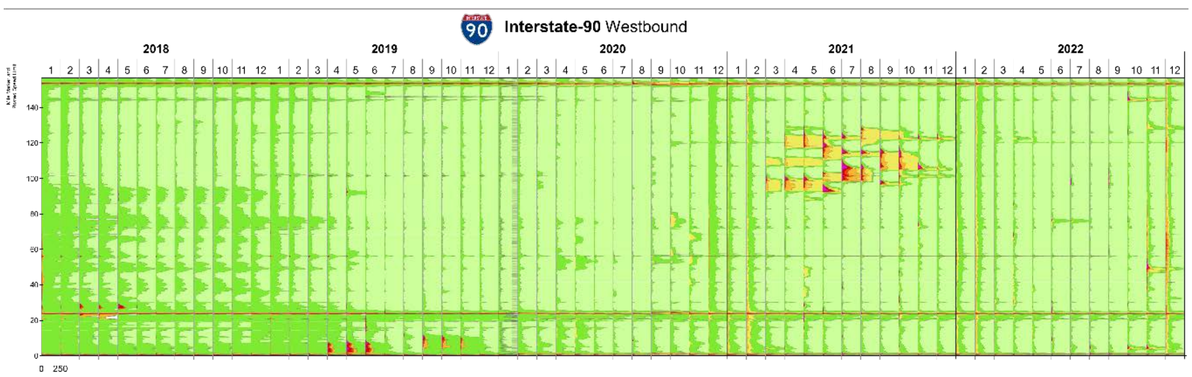
B.8 Interstate 94





B.9 Interstate 90 (Toll Road)





About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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